SAND2006-3083

Advanced Battery Readiness
Ad Hoc Working Group Meeting

Wyndham Washington Hotel
Washington, DC
March 22-23, 2000

Reclamation/Recycle Sub-Working Group
Supplement and Update
December 1, 2000

Forward

This volume forms a record of the Minutes of the Reclamation/Recycle Sub-Working Group of the Department of Energy Advanced Battery Readiness ad hoc Working Group for the meeting that was held on March 22-23, 2000. A list of the Sub-Working Group participants with their contact information is also provided. Updated information has been included for several of the presentations given to the Sub-Working Group in order to bring them current through the end of November 2000. Questions regarding these Minutes or the Sub-Working Group in general may be directed to Rudolph Jungst, Sandia National Laboratories* MS0613, P.O. Box 5800, Albuquerque, NM 87185-0613.

Rudolph G. Jungst
Reclamation/Recycle Sub-Working Group Chairman

*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Advanced Battery Readiness Ad Hoc Working Group

Battery Reclamation/Recycle Subworking Group Meeting Summary

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Agenda

March 22, 2000

1:30 *California ZEV Program Update* - Tom Evashenk, California Air Resources Board
2:00 *EV Battery Recycling Infrastructure Issues* - Todd Coy, Kinsbursky Bros.
2:15 *Battery Recycling and Life Cycle Costs* - Linda Gaines, Argonne
2:45 *Recycling of Nickel Bearing Scrap* - Peter Kuck, US Geological Survey
3:00 *Lithium Market/Supply News* - Joyce Ober, US Geological Survey
3:15 Break
3:30 *Battery Recycling at INMETCO* - Ken Money, INMETCO
4:00 *HPS - High Purity Lithium from Spent Lithium Battery Materials* - Joe Kejha, Lithium Technology Corporation

March 23, 2000

8:00 *Used Ni/MH Batteries for Rural Electrification in Mexico* – Paul Gifford, GM Ovonic
8:30 *Ni/MH Battery Recycling Status and Needs* - Rudy Jungst, Sandia
9:00 *Lithium Battery Recycling Status and Needs* - Rudy Jungst, Sandia
9:30 *Recycling Readiness Chart Update and New Action Items* - All
10:15 Break

Summary

An update on the California ZEV program was presented. The most recent program review occurred in September 2000 but was not a regulatory review. This means that no changes were made to the program at that time. California rules for handling hazardous waste were also discussed. An emergency Universal Waste Rule has been adopted on an interim basis in California in order to provide a single standard. Information on recycling and life cycle costs was presented for the nickel/metal hydride and lithium-ion battery systems. For AB_2 type Ni/MH batteries, the value is in the nickel and in the metal hydride alloy. In the Li-ion case, the cathode is responsible for most of the value, unless a manganese oxide cathode is used. Prices and market trends for some of the more important battery materials were reviewed. Nickel prices have recovered from the depressed levels of 1998, and have been relatively stable over the past year. Commodity recycling flow diagrams are being developed by the US Geological Survey for several metals, including nickel. A facility in Argentina that was scheduled to open last year for the production of lithium from a brine source is now permanently closed. However, lithium prices have remained relatively stable. The operation of the INMETCO battery recycling capability was reviewed. Expansion of the cadmium recovery facility at INMETCO has increased capacity by 75% for that material. The complex set of factors that governs recycling economics was discussed. Lithium Technology Corporation and Pacific Lithium Ltd. will merge early next year. A membrane process developed by Pacific Lithium to purify lithium recovered from scrap batteries was discussed. The process currently operates on a laboratory scale in a batch mode, and an energy study projects that it will be cost effective. A new project by GM Ovonic to field used Ni/MH batteries from EVs for rural electrification in Oaxaca Mexico was described. This is primarily seen as a way to mitigate the high initial cost of this battery system. The entire Sub-Working Group discussed the status and future needs for comprehensive recycling of nickel/metal hydride and Li-ion batteries.

Presentation Summaries

Tom Evashenk - CARB

The next ZEV program review by the Air Resources Board will be in September of 2000. This will not be a regulatory review, so no changes will be made to their program at that time. CARB will assess automaker status on development of ZEVs and reexamine issues such as costs and benefits. The program is strongly supported by the new CARB chairman, Dr. Allen Lloyd. There has been a general downward trend in ozone levels in the LA basin, although the daily VMT is still increasing faster than the population and therefore remains a concern. The emphasis continues to be on zero-emission vehicles, but since 1998 near zero-emission technologies have also been playing a role. Currently, the program includes near-term MOAs with the vehicle manufacturers and a 10% of vehicles offered for sale requirement is still in place for the year 2003. There is presently a total of about 2000 ZEVs statewide in California and about 200 more are anticipated over the next year. For major vehicle manufacturers, at least 40% of their requirement must be fully ZEV, while the remainder can be made up with partial ZEV vehicles. In 1998 a ZEV-like category was also added to the program since hybrid vehicles of various types are coming out and will have to be factored in. Fuel cells are viewed as not being available for cars for a few years yet. The 2003 requirement amounts to a need for an annual market of about 22,000 true ZEVs in California. A report on Task 2 of an assessment for CARB of health impacts of reclamation of automotive batteries has now been issued. The broad conclusion is that advanced batteries are a significant improvement over lead-acid in terms of recycling impacts. CARB has also rehired Fritz Kalhammer to chair a four-member panel that will update progress in battery development. A draft final report will be presented at the May 2000 workshop. Over 500 charging stations are presently operating in California. These are funded by businesses and therefore are free to use right now; they will cost later on.

<u>11/2000 Update</u>

The 2000 Zero Emission Vehicle Program Biennial Review was held on September 7 and 8, 2000. This review was regarded as important even though it was not a regulatory review since the MOA period in California (calendar years 1998, 1999 and 2000) is now ending. It also provided a final opportunity to assess the automaker's readiness for the regulations slated to go into effect in 2003 since the lead time to introduce new vehicles for production is usually about 3 years. The meeting provided an opportunity to put together information from the MOA experience, meetings with the vehicle manufacturers, assessments by outside experts, and feedback from public workshops. In general, satisfaction with the performance of the EVs that have been leased or sold in California over the last three years is very high. Moreover the total number of about 2300 on the road there today exceeds the MOA commitment (assuming multiple credits for advanced batteries). However availability of ZEVs is currently very low because most manufacturers who have met their MOA quotas have now stopped production due to the fact that the vehicles are unprofitable and the market is uncertain. Unfortunately, this lack of availability also prevents the current demand for ZEVs from being quantified.

Market assessment is viewed as the one area in which it is most difficult to obtain reliable estimates of what to expect when implementing the 2003 requirements. The ZEV program will require about 22,000 electric vehicles in 2003. This is almost a 10-fold increase over present numbers. Another area of uncertainty is how many PZEVs can be built by 2003 so that the full number will not have to be pure battery electric vehicles. To date only one vehicle has achieved full PZEV status. Hybrid vehicles could also contribute to the reduced emissions if the necessary emission controls can be perfected in time. Hydrogen powered fuel cell vehicles could become another class of ZEVs, but are not expected to be commercially available by 2003. Batteries are the single most costly component of electric vehicles. Ni/MH batteries were judged to be the best advanced technology in terms of performance and life, but are high in cost. Other concerns are the infrastructure of charging stations that will be necessary to obtain public acceptance. Cost and consumer acceptance are viewed as the two major barriers at this point. Although ZEVs have issues of their own, such as creating new waste disposal needs, their impact on reducing air emissions is viewed as the greatest per vehicle and they are the only technology that is guaranteed to permanently reduce emissions over time.

At the conclusion of the review, the Air Resources Board passed a resolution directing the staff to address some of these challenges. In particular, the Board called for modifications addressing the need for product availability and market stability, enhancement of public awareness and education as to the benefits of ZEV technology, and the mitigation of the high initial costs of the vehicles and batteries in low volume production. These were seen as the greatest needs for the long-term implementation of the ZEV program. Proposed changes are to be brought back to the Board on January 25, 2001.

Todd Coy – Kinsbursky Bros.

Todd reviewed the Kinsbursky Bros. battery collection capability and their permits for this activity. They are now developing a nationwide collection capability, including the necessary supporting documentation. Todd has been investigating whether EV batteries are hazardous waste (ignitable, reactive, corrosive, or toxic), but they are definitely solid waste. California has its own set of special categories in this area, such as for nickel. The Federal Universal Waste Rule (1995), part 273, deregulated some waste management practices. Each state that had no program of its own had to individually adopt this Rule and currently only 43 states have done so. In response, Congress passed Public Law 104-112, which excepted certain battery chemistries from regulation (Hg, Ag, Zn, Ni/Cd), but not lithium. California very recently passed an emergency Universal Waste Rule of their own as an interim solution until a permanent rule can be adopted. This applies to batteries that would otherwise be considered hazardous waste. New regulations must be in line with Public Law 104-142 but can be more stringent than part 273. The benefit of all this is that now there at least is a single standard. One caveat is that a damaged battery is <u>not</u> universal waste and may be considered hazardous waste. Todd will continue to monitor activity in California and examine the regulatory status in other states, which usually mirrors the Federal Universal Waste Rule.

11/2000 Update

California has not adopted a permanent Universal Waste Rule and the emergency Universal Waste Rule remains in effect as of mid-November 2000. Numerous workshops were held over the summer and fall to explain the emergency Rule, which is patterned after the Federal Universal Waste Rule. However, no permanent Rule document copies have been distributed yet and the permanent Rule adopted may end up deviating somewhat from the Federal Rule. Todd is not aware of any deadline for replacement of the emergency Universal Waste Rule. Although there is some legislative activity in California to compel recycling for certain listed wastes, there is currently no requirement to recycle universal waste such as EV batteries.

Linda Gaines – Argonne National Laboratory

Linda discussed a Ni/MH battery life cycle analysis done for USABC and also lithium-ion battery life cycle costs. These batteries contain new materials to target for recovery. The presentation did not address reuse, regulations, who's responsible for collecting the batteries, etc. Ease of separation continues to be an issue. Larger cells are generally easier to disassemble. Lithium batteries (especially Li-polymer) will be more difficult to disassemble and physically separate than Ni/MH batteries because of thin electrodes. Lithium-ion batteries for HEVs will use even thinner active material layers.

It usually is best to recover materials in as close to a usable form as possible to minimize processing and maximize value of the recovered product. For AB_2 Ni/MH batteries, the value is clearly in the Ni and the metal hydride alloy. In general, the cathode is expected to constitute most of the value in Li-ion cells unless manganese oxide is being used. The separator and electrolyte are two other potentially high-value components. $LiPF_6$ is ~$55/lb., although the price may drop if high quality product appears from more manufacturers. The separator cost is high (~$80/lb.), but the basic material is quite inexpensive ($.60/lb.), and it would be difficult to recover any of the value added from fabrication, so there may be less chance for gain there. Processing costs for Li-ion battery recycling are quoted as being ~$2/lb.

A comment was made from the audience that three properties required for efficient recycling are large volume, uniformity of product, and usability. In their opinion, neither volume nor uniformity is sufficient at this time to justify electrolyte recovery from lithium-ion batteries. Another comment expressed was that repurification of $LiPF_6$ would probably cost more than it is worth. The question of the need for cryogenic processing of Li-ion batteries containing intercalation anodes was also discussed. This is considered a prudent safety practice since some plating of Li may occur if charge control fails. Recovery of unaltered cathode material was also seen as unlikely, although it probably wouldn't become hazardous waste.

Peter Kuck - U.S. Geological Survey

Peter reviewed recent trends for nickel supply and pricing. New sources of supply in Australia, Canada, and other key producing countries were discussed together with projected capacities. Three nickel laterite mines were commissioned in Western Australia in 1999CBulong, Cawse and Murrin Murrin. The nickel and associated cobalt were being recovered onsite using advanced pressure acid leach (PAL) technology. All three operations had to overcome startup problems associated with the new technology. The principal problem was unanticipated corrosion inside the autoclaves, transfer valves, and associated piping. At least three other Australian PAL projects are in varying stages of development. Industry competitors are considering employing PAL technology in Cuba, Indonesia, New Caledonia, and the Philippines.

In Canada, development of the huge Voisey's Bay nickel-copper-cobalt sulfide deposit near Nain was still in limbo. Inco Limited-the project sponsor-and the Provincial Government of Newfoundland and Labrador were unable to reach agreement on critical concepts and suspended negotiations in January 2000. Exploration crews will continue to drill the deposit from the surface, evaluate neighboring anomalies, and conduct geophysical surveys throughout the Voisey's Bay district. Drilling crews are exploring several other promising districts in northern Canada-the Lac Rocher region southeast of James Bay, the Ungava Nickel Belt in northern Quebec, and an area in Manitoba northeast of the Thompson Nickel Belt. New ore bodies also have been found in and around existing mines in the Sudbury district of Ontario.

Austenitic stainless steel accounts for two-thirds of the primary nickel consumed in the world. Since 1975, demand for stainless has grown at an average rate of 4.5% per year. This growth rate is projected to continue or accelerate over the next 20 years. World nickel demand continued to grow faster than supply in 2000, causing a gradual drawdown of stocks in warehouses approved by the London Metal Exchange (LME). Producer stock levels, though, were relatively unchanged because mine production was at an all-time high. Resumption of economic growth in parts of East Asia and strong demand for stainless steel in the European Union and the Americas has kept nickel prices from returning to the depressed levels of 1998. For the week ending November 17, 2000, the LME cash price for 99.8%-pure nickel averaged $7,210 per metric ton ($3.27 per pound). Twelve months earlier, the cash price was $8,031 per ton ($3.64 per pound).

The price of cobalt metal continues to decline, in contrast to that of nickel. Cobalt has dropped from the $30/lb range to about $14/lb. World cobalt production is expected to increase significantly in the next few years, when the Australian laterite projects begin reaching planned production levels.

Several automobile manufacturers are using nickel-metal hydride (Ni-MH) batteries to power their gasoline-electric hybrid and pure electric vehicles for the 2001 and 2002 model years. Japanese manufacturers of nickel-based batteries-consumer, industrial and automotive-used an estimated 22,000 tons of nickel in 1999. *(This last estimate is a projection of data compiled by Heinz H. Pariser & Co., 2000).*

The USGS is preparing commodity recycling flow charts for a number of metals. The chromium report is almost completed, and reports on nickel, cobalt, and manganese are in progress. Collection and recycling of nickel scrap were also discussed. Nickel scrap is handled in a step system where opportunities to recycle become increasingly limited with each step downward. More efficient ways to disassemble batteries would be beneficial. Establishment of a second INMETCO-like facility in a different region of the country may be justified at some point.

A final issue raised was the disposition of ~ 6,000 tons of slightly radioactive nickel scrap owned by DOE. Current perception is that it would be unacceptable to recycle any of the DOE nickel into consumer products. The steel industry has zero tolerance for radioactive scrap because of bad experiences in the past, and battery manufacturers would likely adopt a similar position.

World Mine Production, Reserves, and Reserve Base:
(metric tons of nickel content)

	Mine production		Reserves	Reserve base
	1999	2000		
United States	-	-	43,000	2,500,000
Australia	126,000	167,500	9,100,000	11,000,000
Botswana	25,800	24,200	780,000	830,000
Brazil	43,784	43,900	670,000	6,000,000
Canada	188,218	194,000	6,300,000	15,000,000
China	50,100	51,900	3,700,000	7,900,000
Colombia	39,300	55,500	560,000	1,100,000
Cuba	64,407	68,700	5,500,000	23,000,000
Dominican Republic	39,500	44,700	720,000	1,300,000
Greece	16,050	20,900	450,000	900,000
Indonesia	89,100	93,500	3,200,000	13,000,000
New Caledonia	110,062	120,000	4,500,000	15,000,000
Philippines	8,450	20,700	410,000	11,000,000
Russia	260,000	265,000	6,600,000	7,300,000
South Africa	35,802	32,800	2,500,000	12,000,000
Venezuela	-	3,200	610,000	610,000
Zimbabwe	11,164	9,900	240,000	260,000
Other countries	12,412	9,300	450,000	12,000,000
World total (rounded)	1,120,149	1,225,700	46,000,000	140,000,000

Joyce Ober – U.S. Geological Survey

Changes in the lithium market were briefly updated. The news last year was a new FMC operation in Chile, using a brine source. That facility, which used a non-standard ion exchange process for lithium recovery rather than evaporation, is now closed. Some lithium suppliers have raised prices while at the same time production cuts in Russia and China are rumored as a result of other cheaper material from Chile. Overall prices are relatively stable and supply is ample.

Ken Money - INMETCO

Ken money from INMETCO reviewed the history and capabilities of the INMETCO facility. INMETCO was established in 1976 to recycle flue dust, cake, baghouse dust, etc. for the stainless steel industry. A wide range of battery chemistries is also accepted for recycling. Approximately 5 years ago INMETCO established a cadmium recovery facility it its site and this was expanded by 75% in March 2000. Seven cadmium furnaces are now running 24 hours/day. About 70,000 tons of material is processed per year and 100,000 gallons of spent liquids are consumed per month. In the case of small consumer Ni/Cd cells (sealed), thermal oxidation is used first to remove all of the organics and moisture. The cadmium is then distilled off and the recovered Cd shot is recycled to the Cd market. The residue is smelted and then goes to the stainless steel industry. Larger industrial batteries are physically separated into their positive and negative plate components. The cadmium negatives are distilled as before and the positive nickel plates are smelted and then are sent to the stainless steel industry. Health, safety, and regulatory issues were discussed. These include Federal, State, and possibly international regulations, the Universal Waste Rule, transboundary movement of material, the Basel Convention, and local employee safety considerations. Factors important to the economic feasibility of battery recycling are the chemistry, amount of material available, value of the products, sorting required, revenue generated, customer service base, etc. The economics depends on both internal and external cost factors. In the final analysis, it must be made easy for the customer to recycle and costs must be acceptable. Customer education is also important. In response to a question about market saturation from a large number of EV batteries, Ken stated that INMETCO is able to sell all of the product it recovers now. Only 10-15% of their work is currently battery related. They may eventually pay for Ni/MH batteries at high volume, but not for Ni/Cd. At present there are no regulatory issues with return of RBRC consumer batteries. However, more focus is needed on getting the customers to actually recycle their batteries since the percentage returned remains low (about 30%). A comment was made regarding the need for better battery marking when returning them. Right now INMETCO uses a combination of automated and manual processing for plate separation. Completely automated processing requires a more consistent battery shape.

Joe Kejha – Lithium Technology Corporation

Pacific Lithium Limited and Lithium Technology Corporation are merging into a new company to be called ILiON. Pacific Lithium Limited product is in 25% of the lithium batteries in Japan. The process they use to recycle Li involves freezing and then reacting with alkali to safely deactivate the lithium. The water-soluble part that results is composed of 12.8% Li, 1% OH^-, 1.9% Cl^-, 0.4% metals, 83.9% S_xO_y, and a variety of metals on the ppm level. Electrolysis of this waste produces purified LiOH, which can be converted to

Li_2CO_3 by carbonation. They have investigated the best membrane and most efficient electrodes to reduce voltage drop and reduce energy use during electrolysis. The product has most impurities reduced to below 10 ppm. When the electrolysis cell voltage climbs, it indicates that purification has been completed. Further improvements to the process are still needed and other materials may be recoverable from lithium battery by-products. In response to questions, Joe stated that they have processed mostly material from lithium primary batteries at this point. The device is a small laboratory prototype now, but it will be scaled up to pilot production size. Based on their energy study, the process is cost effective.

Paul Gifford – GM Ovonic

GM Ovonic has been investigating ways to bridge the cost barriers for Ni/MH batteries. Costs of $200-250/kWh exceed the automotive cost targets for widespread commercialization of battery-powered cars. Not as much value is obtained for scrap batteries as one might think, especially since much of the value-added material cost cannot be recovered. However, since Ni/MH batteries fail more rapidly due to power fade than capacity fade, a used Ni/MH battery still has better performance than lead-acid. GM Ovonic has been engaged in a joint demonstration program with USSC on rural electrification. USSC (United Solar) is a joint venture between ECD and Canon that produces thin-film amorphous photovoltaic cells and PV storage systems. Ni/MH batteries can be placed in secondary uses at a marginal premium over flooded marine lead-acid ($50-150/kWh). Mexico, with its large rural population, had the most response to the joint venture and a pilot demonstration project was set up in the State of Oaxaca. Battery modules recovered from packs used in EVs for 10-15,000 miles up to 40,000 miles are being tested in the demonstration. They are now talking with the World Bank about a potential $100 M project. Very efficient fluorescent lighting systems can be powered on 30 W from one standard GMO 900 module (13.2 V). It isn't known for sure at this point how much battery life is left, but the business case has been built around 3 years. Costa Rica is another potential site, since it is trying to attract tourists and is being promoted as ecologically friendly. GM Ovonic's current interest is in doing a low-cost battery design for this application rather than having to wait for used batteries. The question was raised whether the same approach could be taken with lithium-ion batteries. The main problems are still the base cost of the batteries and PV system, and the cost/reliability of the electronic controls needed to prevent overcharge. Near term, GM Ovonic is planning an additional 20 to 30 systems for installation in Oaxaca. Ultimately, the volume of batteries reused in this way could be significant, since there are large population areas with no access to electricity. GM Ovonic is talking with the World Bank and others about a potential $100M project.

<u>11/2000 Update</u>

GM Ovonic just had a follow-up meeting with its partners in Mexico on this project the week of November 13th. Testing of a lab system at the Mexico energy institute IEE has been successfully completed. Currently, a total of 28 solar home systems has been installed in the state of Oaxaca, Mexico and is performing well.

Ovonic is now in the process of installing 85 additional systems into Oaxaca to provide full electrification to a rural village ("model community"). These batteries represent "spent" EV batteries from different testing or vehicle validation projects. There is an immediate need for ~ 8000 units in Oaxaca alone. The challenge is to create a business case and to explore creative means of financing the higher initial cost of systems with advanced batteries.

General Discussions

The entire Sub-Working Group discussed the status and future needs for comprehensive recycling of nickel/metal hydride and lithium-ion batteries. Reuse of components from nickel/metal hydride cells, although attractive from a recycled value standpoint, was viewed as unlikely to occur because of difficulty and high cost involved in refurbishment of worn out batteries. It was suggested that it would be preferred to recycle metal hydride alloys through the alloy manufacturer since it is believed that some remelt can likely be tolerated in the process. However, the effect of impurities accumulated in the materials during use of the battery and the amount of recycled material that can be incorporated in the process without degrading the final product are unknowns at this point. Some battery sorting and disassembly is probably desirable and can be supported for high numbers of relatively large batteries.

Most of the discussion about recycling the lithium-ion battery system revolved around the cathode material. Although the value of cobalt is sufficient to make its recovery economically justifiable, alternative metals such as nickel and manganese that may be used in cathodes have lower value. More information is needed regarding the value of manganese oxide and potential markets for it as well as the recovery cost so that a break-even point can be estimated. Fluctuation in metal prices could possibly cause the recycling cost of even cobalt and nickel to exceed the value of the recovered product. The recovery and purification of electrolyte salt from lithium-ion batteries versus remanufacture of the salt from lithium carbonate was also discussed briefly. Processing cost is again uncertain, but it appears that purification could be complicated and therefore too costly. Processes for recycling lithium-polymer batteries are being developed, but the details are considered proprietary at the present time. A renewed effort should be made to obtain information in this area.

Action Items

Old action items and their disposition:

> Continue to follow EPA data gathering on solid waste definition issues. EPA was invited to attend the meeting but was unable to do so. Information was obtained on the new California emergency Universal Waste Rule.
>
> Maintain contact with CARB and update possible revisions to the CARB ZEV Program for 2003. A presentation on results of the ZEV Program was made at the

meeting and progress toward the goals for 2003 was discussed. EV population estimates were presented and compared to the program goals.

Continue to follow work by Sony to enhance Li-ion battery recycling capability. Sony was unable to attend this meeting, but contact will be maintained for future presentations.

Review battery collection and recycling infrastructure in Europe and Japan. Appropriate representatives knowledgeable in these areas were invited to the meeting, but did not attend.

Request briefings on alternative methods for recycling Li-ion and Li-polymer batteries from battery developers. Developers were invited to the meeting and some attended, but did not present. A briefing on the Li salt recovery process from battery waste was scheduled, but could not be accomplished at this meeting. Work going on for Li-polymer is not yet available for public discussion. Presentations may be possible at the meeting next year.

Evaluate the feasibility for recovery of both lithium and cobalt (or other cathode metals) from Li-ion batteries. Information was obtained at the meeting regarding the economic benefits of recovering various materials from Li-ion batteries. More work needs to be done to refine estimates of potential value and define processes.

Promote the development of more comprehensive Ni/MH battery recycling processes. The existing methods for recycling this battery chemistry were reviewed again and possible additional materials to recover were discussed from both feasibility and economics perspectives. Updating the 1994 NREL/A. D. Little report on the feasibility of Ni/MH battery recycling would be a useful step toward identifying specific areas where further research is needed.

Refine estimates of metals content for the major species expected in Li-ion and Ni/MH batteries. Some additional information was obtained at the meeting and the updated Ni/MH recycling report will fill the gap for that chemistry. The US Geological Survey is preparing commodity recycling flow charts for specific metals and this information would also be useful for that effort.

New action items from this meeting are as follows:

Continue to follow the California ZEV program results as the year 2003 target approaches.

Reinforce efforts to obtain information on battery collection and recycling procedures in Europe and Japan.

Evaluate the influence of HEV introductions on the EV/HEV population and recycling needs.

Request updates and reports on other lithium-ion and lithium-polymer battery recycling approaches that are being developed.

Continue to request information on EPA solid waste definition projects.

Obtain information on hydride alloy properties, impurity tolerance, and potential markets for reclaimed material. Some electrode analysis may be needed.

Collect information about markets for recycled rare earth materials.

Define the cost of cathode and electrolyte material recovery from the lithium-ion battery system more clearly.

Attachments

Thomas Evashenk
California Air Resources Board

Zero Emission Vehicles: The California Perspective

Thomas Evashenk
California Air Resources Board

Advanced Battery Readiness Working Group
March 22-23, 2000

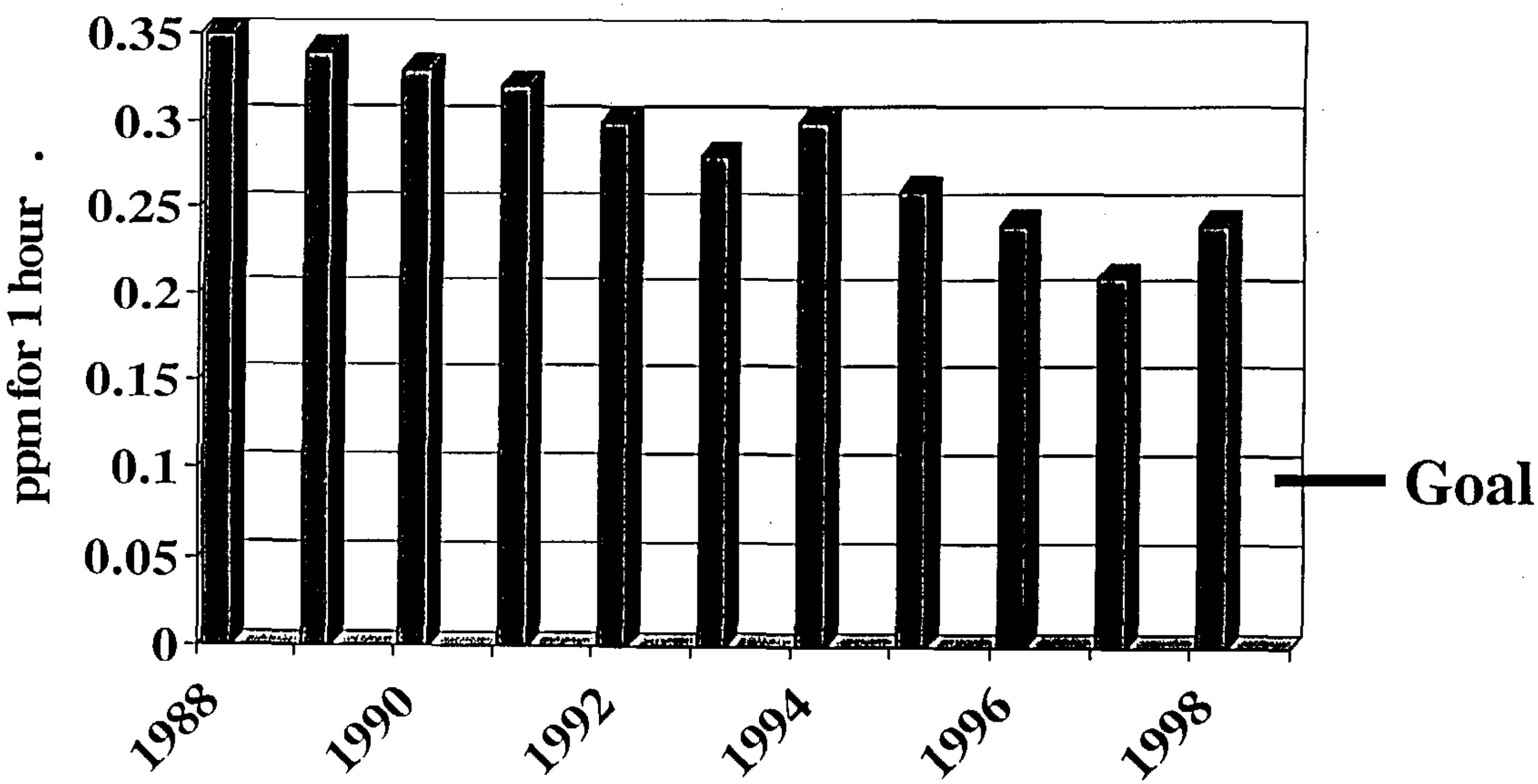
California Environmental Protection Agency
Air Resources Board

Outline

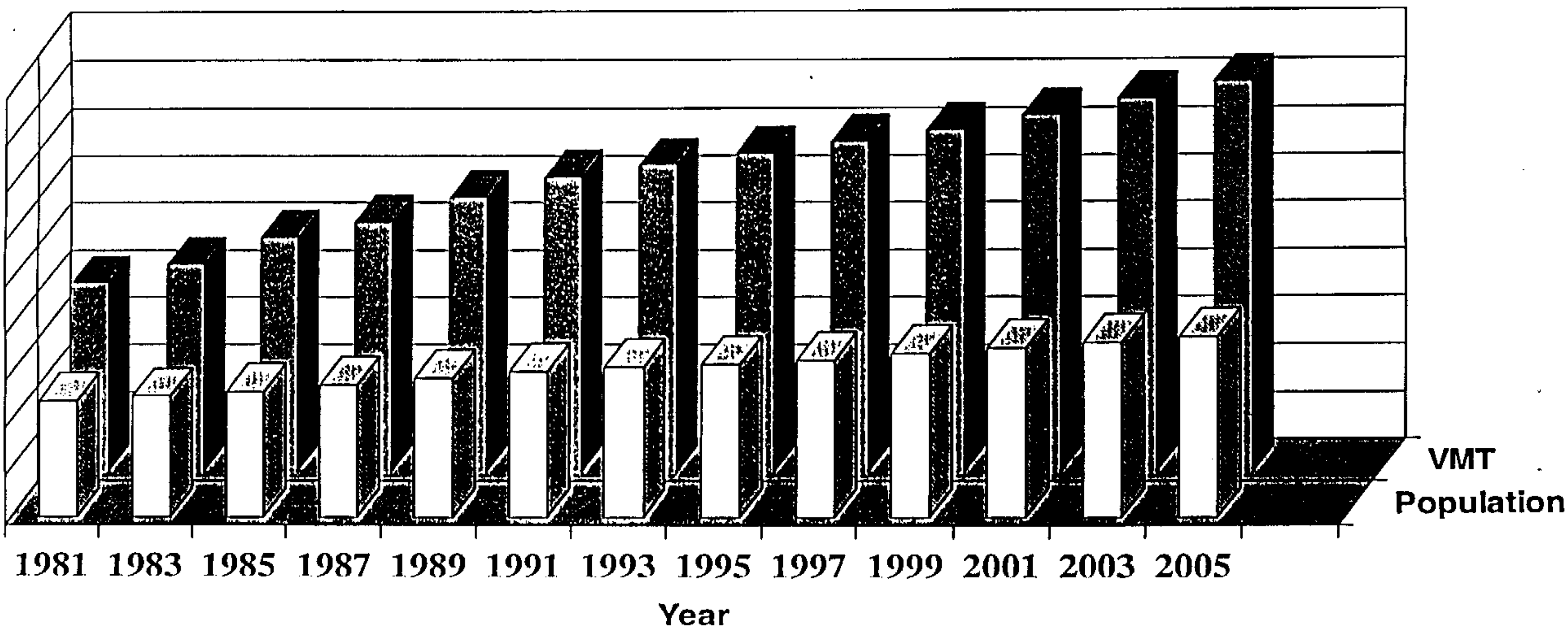
- Background
- Low Emission Vehicle Program
- 2000 ZEV Review
- Next Steps

Air Quality Is Improving

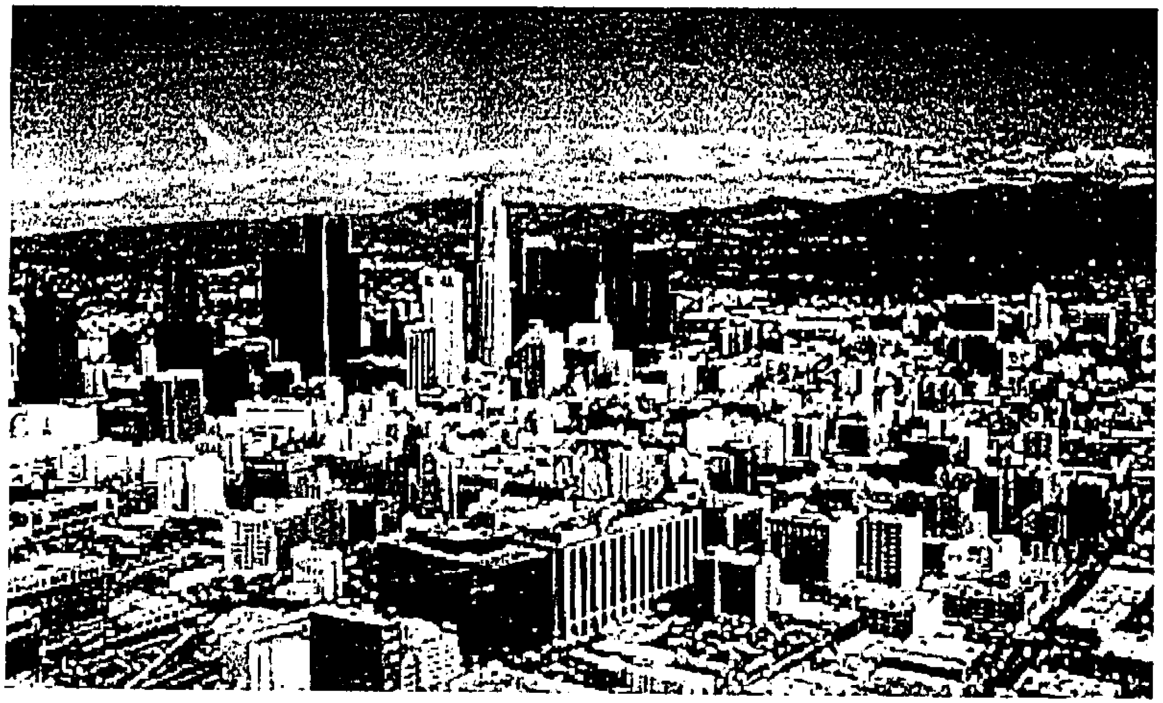
Highest Ozone: Greater Los Angeles



Daily VMT Increasing Faster Than Population



Long-Term Vision



- Continued Emphasis on Zero Emissions
- Near-Zero Technologies Also Play Major Role

Continued Emphasis on ZEVs

- No Tailpipe Emissions
- No Evaporative or Refueling Emissions
- No Emissions Deterioration
- Indirect Emissions Extremely Low in California

Recycling Contract

- Task 1: Completed March 1995
- Task 2: Completed April 1999
  - compared relative impacts of recycling: toxicity, flammability, corrosivity etc.
- Semi-qualitative ranking used to assess relative impact to health/environment
- Broad conclusion: advanced batteries represent significant improvement over lead-acid batteries in terms of impacts from recycling

Battery Technical Advisory Panel

- Four member panel contracted to assess cost of advanced batteries in 2003 and 2008 timeframes
- Panel to gather information from all major suppliers and automakers
- Draft final to be presented at May 2000 workshop

Current Statewide ZEV Population

Manufacturer	Model	Battery Type	Lease Cost ($)	City Range	Highway Range	Number Placed
Daimler Chrysler	EPIC	PbA	NA	70	65	17
	EPIC	NiMH	450	92	97	97
Ford	Ranger	PbA		84	69	51
	Ranger	NiMH	450	94	86	308
GM	EV1	PbA (Ovonic)	349	75	78	460
	EV1	PbA (Panasonic)		111	113	
	EV1	NiMH	449	143	152	
	S-10	PbA		46	43	110
	S-10	NiMH	440	92	99	76
Honda	EV Plus	NiMH	455	125	105	330
Nissan	Altra	LiIon	599	120	107	37
Toyota	RAV4	NiMH	492	142	116	486

Total: ~ 2,000 vehicles

2003 Requirement

- Roughly, one percent of CA light-duty sales equals 10,000 vehicles
- Projection assumes:
  - automakers meet 60% percent of ZEV obligation with partial ZEVs
  - 2003 production is equal to 1998
  - automakers do not obtain early credits
- Expected market: 22,000 vehicles

Emerging Technologies

- Hybrid Electric Vehicles
  - With No "All Electric Range"
    - 2000 Honda Insight, Toyota Prius
    - Big 3: Diesel hybrids
    - No urban emission advantages
    - Better efficiency (lower CO_2)
  - With "All Electric Range"
    - Emission advantages of battery EV

Emerging Technologies

- Fuel cell electric vehicles
  - Development programs at all major manufacturers
  - California Fuel Cell Partnership
  - Zero or near zero emissions
  - Infrastructure/fuels issues

California ZEV Program

- Memoranda of Agreement with Automakers
- Ten Percent Sales Requirement for 2003
- September 2000 Air Resources Board Review of ZEV Program

Ten Percent Sales Requirement

- Major Manufacturers
  - At least 40 percent of their requirement must be met by "full ZEV allowance vehicles"
  - Multiple allowances for extended range and early introduction
  - The remaining requirement may be met by "partial ZEV allowance vehicles"

Partial ZEV Allowance Vehicles

- Vehicles with ZEV-like qualities
  - Extremely low tailpipe emissions
  - Zero evaporative emissions
  - Extended durability (150k miles)
  - All-electric range
  - Advanced ZEV components
  - Very low fuel cycle emissions

ZEV Allowance Examples

Fuel/Vehicle System	ZEV Allowance
Gasoline SULEV	0.2
Gasoline HEV, no ZEV range	0.3
CNG SULEV	0.4
Gasoline HEV, 20 mile range	0.6
Methanol Reformer FC Vehicle	0.7
Direct Methanol FC Vehicle	1.0
Stored Hydrogen FC Vehicle	1.0
HEV with 100 mile ZEV range	1.0

LEV II

- New light-duty truck category
- PC/LDT Emission standards
  - 0.05 NOx -LEV, ULEV
  - 120,000 mile durability standard
  - Lower PM standard for diesels
  - SULEV standard for PCs and LDTs
  - Optional 150,000 mile standard
- New fleet averages through 2010

LEV II Modifications to ZEVs

- Partial ZEV credits for qualifying technologies
  - Hybrid-electric vehicles
  - Fuel-cell vehicles
  - Extremely low-emissions vehicle
- New "SULEV" standard
  - 150,000 mile durability/warranty
  - OBDII/zero-evaporative emissions required
- Fuel cycle emissions considered

September 2000 ZEV Review

- Assessment of Automaker Status
- Vehicle and Battery Technology Assessment
  - Battery Panel, focus on cost
- Evaluation of MOA Obligations
- Costs and Benefits
  - Full fuel cycle emissions and energy efficiency

2000 ZEV Review Milestones

- Workshops on March 29, 2000 and May 31, 2000
- Staff Report July 2000
- Board Hearing September 7, 2000

Linda Gaines
Argonne National Laboratory

Battery Recycling Economics

Linda Gaines

for

Advanced Battery Readiness Ad Hoc Working Group

Washington, DC

March 2000

Argonne National Laboratory
Transportation Technology R&D Center

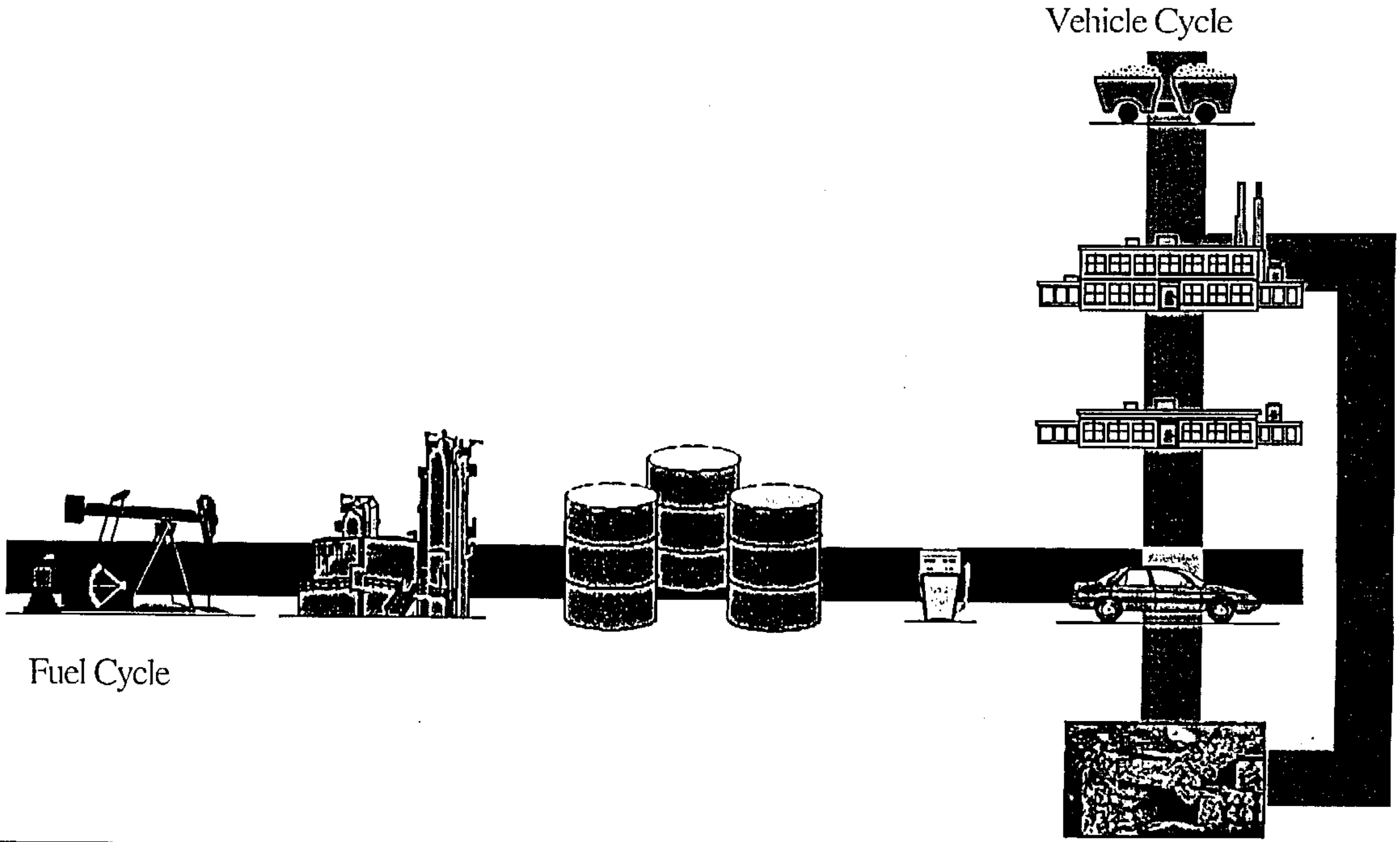
Content of Presentation

- Scope: Ni-MH and Li-ion materials
- General ideas about recycling
- What's in the batteries and how much it costs
- Current recycling practice and economics
- Materials to target for recovery
- Does not address
  - reuse
  - collection and separation issues
  - institutional issues
    - regulations
    - who's responsible

Maximize Value of Recovered Materials

- Examine major contributors to material cost
- Can value added be recovered?
- Basic raw material may have little value
- Try to recover as close to usable form as possible
- Material recovery should make recycling economical
  - value of materials plus avoided disposal costs must exceed recycling costs
  - recovered materials may have lower value and/or cost
  - open-loop or closed-loop recycling acceptable
- Will reduce total lifecycle cost and environmental burdens
  - costly or high-impact steps avoided

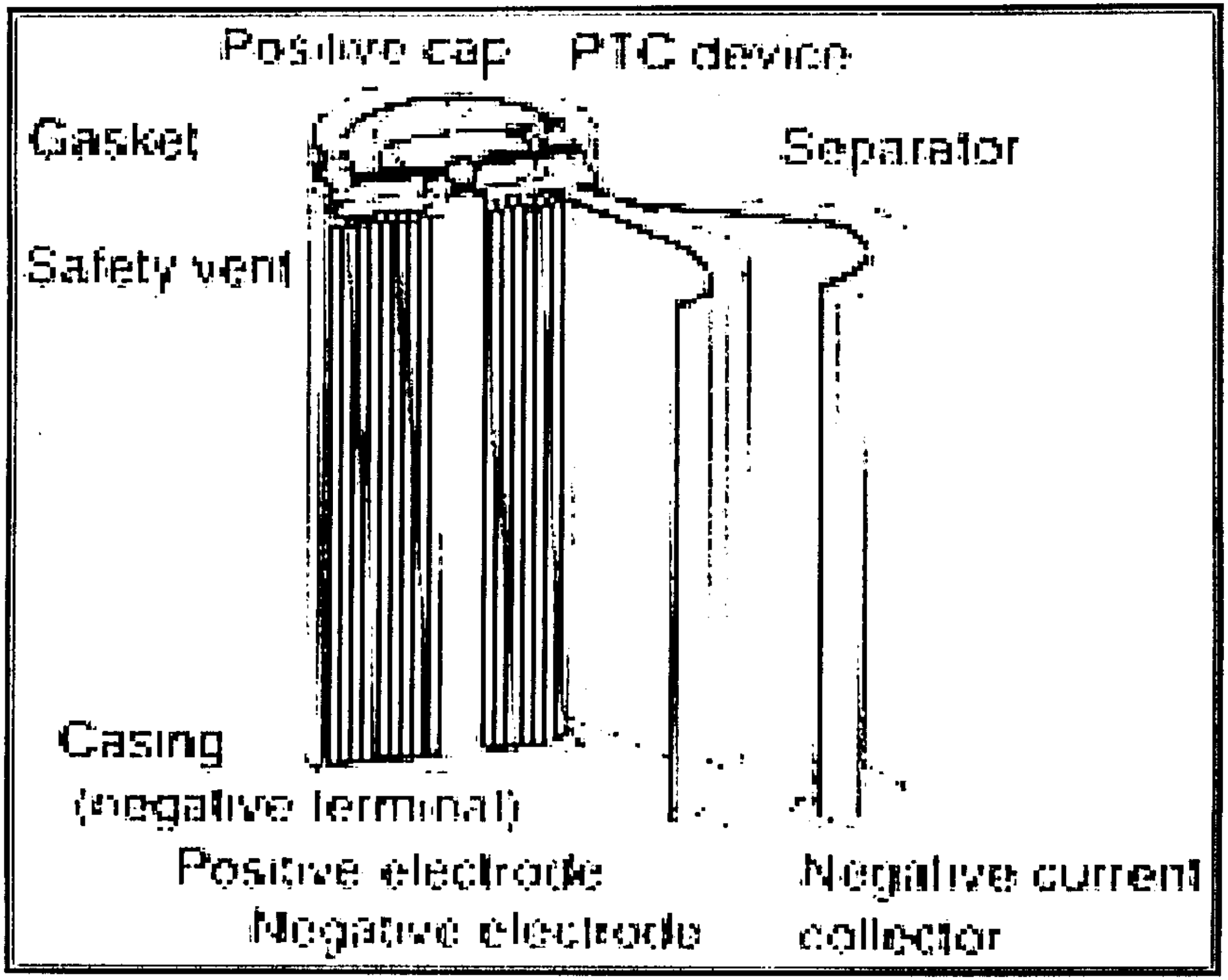
Generic Life Cycle Flow



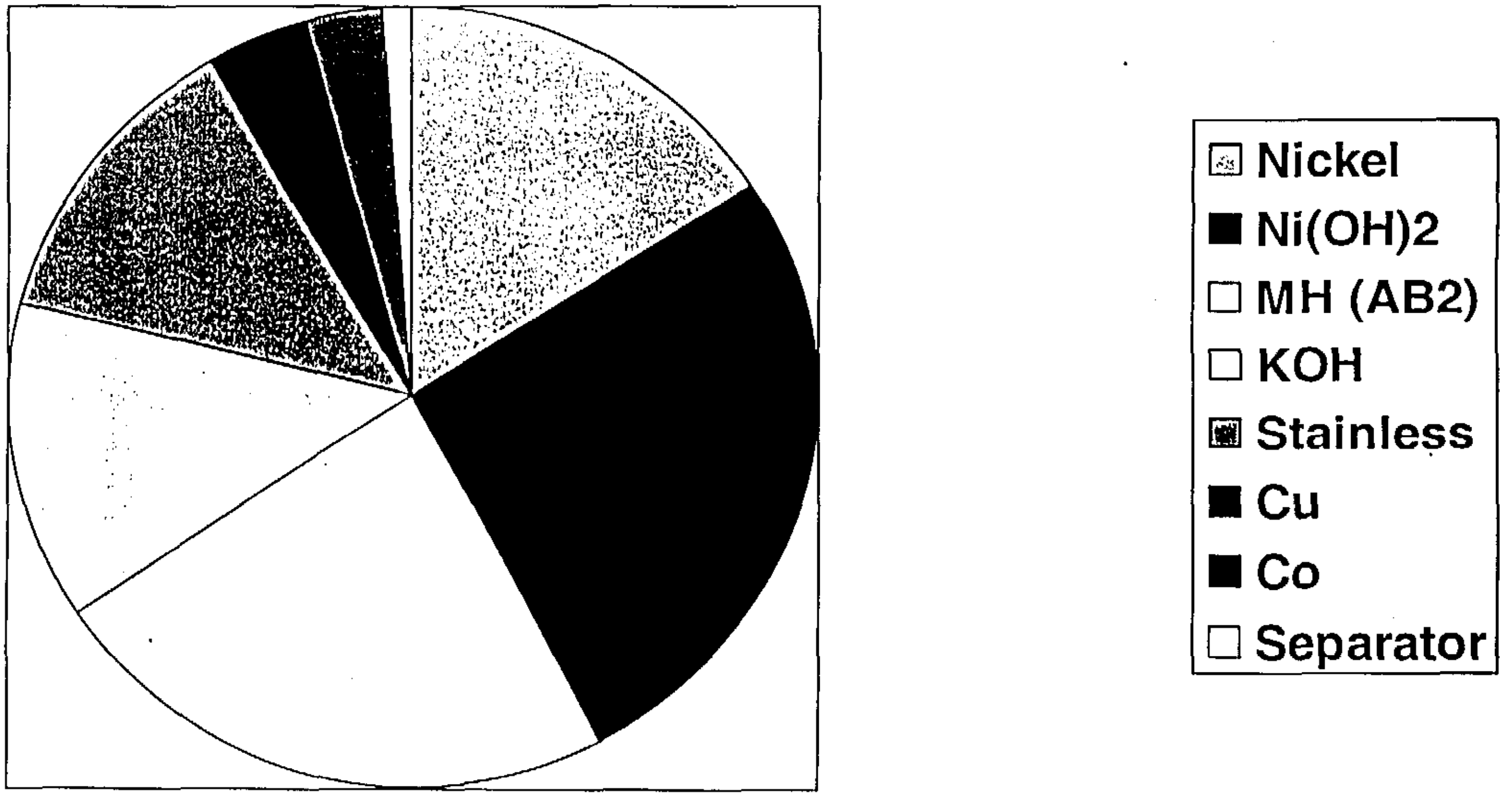
Recycling of Automotive Cells

- Battery pack and module packaging removed first
- Large cells easier to sort by cell chemistry
  - this enables recovery of purer materials
- Large cells easier to disassemble to recover separated streams
- Li-ion cells less amenable to easy disassembly
  - does reactivity demands inert atmosphere or cryogenic treatment?
  - electrode materials laminated together
  - polymer electrolytes and film packaging will compound difficulties

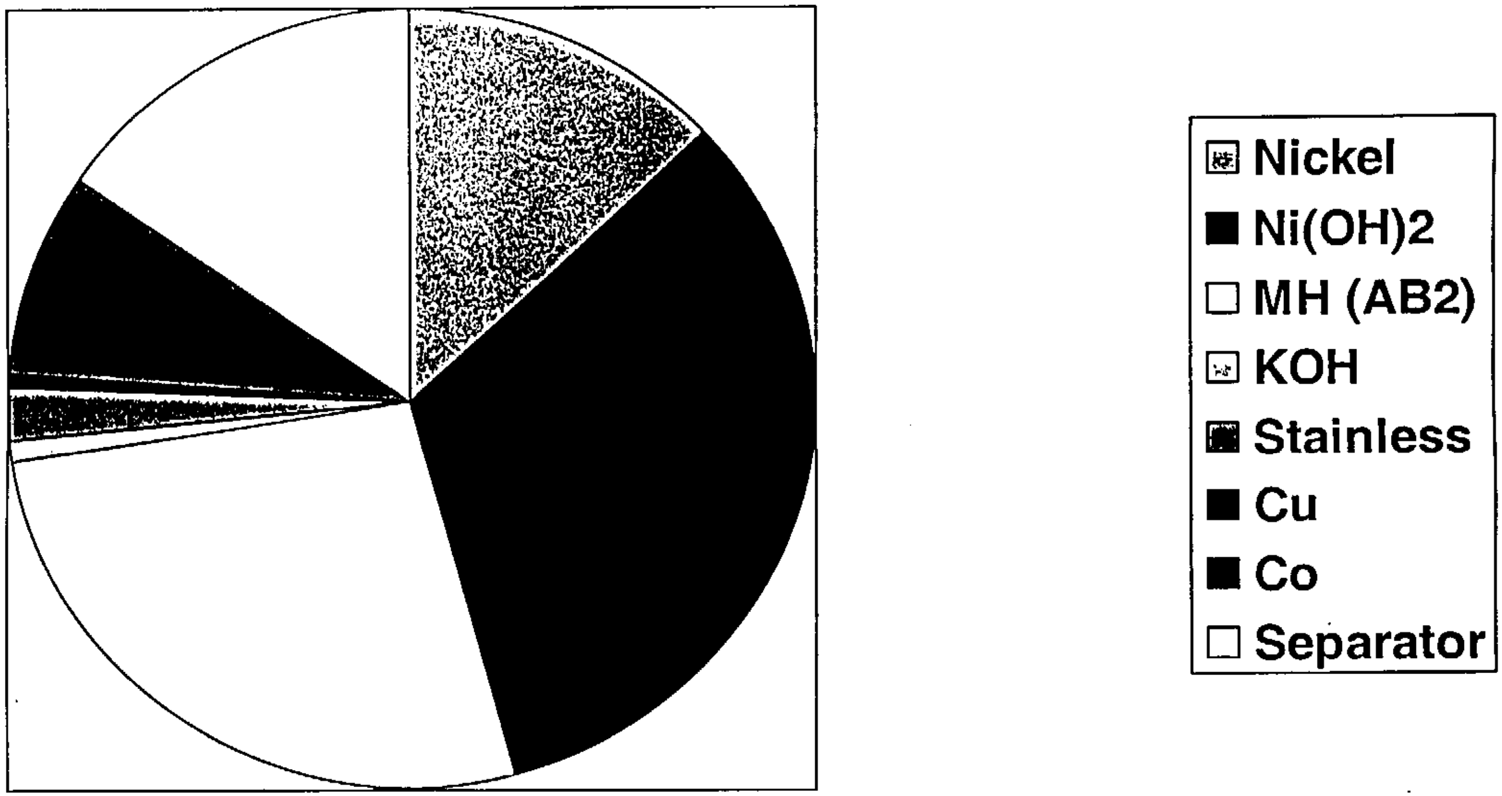
Li-Ion Cell Harder to Disassemble than Ni-MH Cell



What's in a Ni-MH EV Cell



Cost of Materials in Ni-MH EV Cell



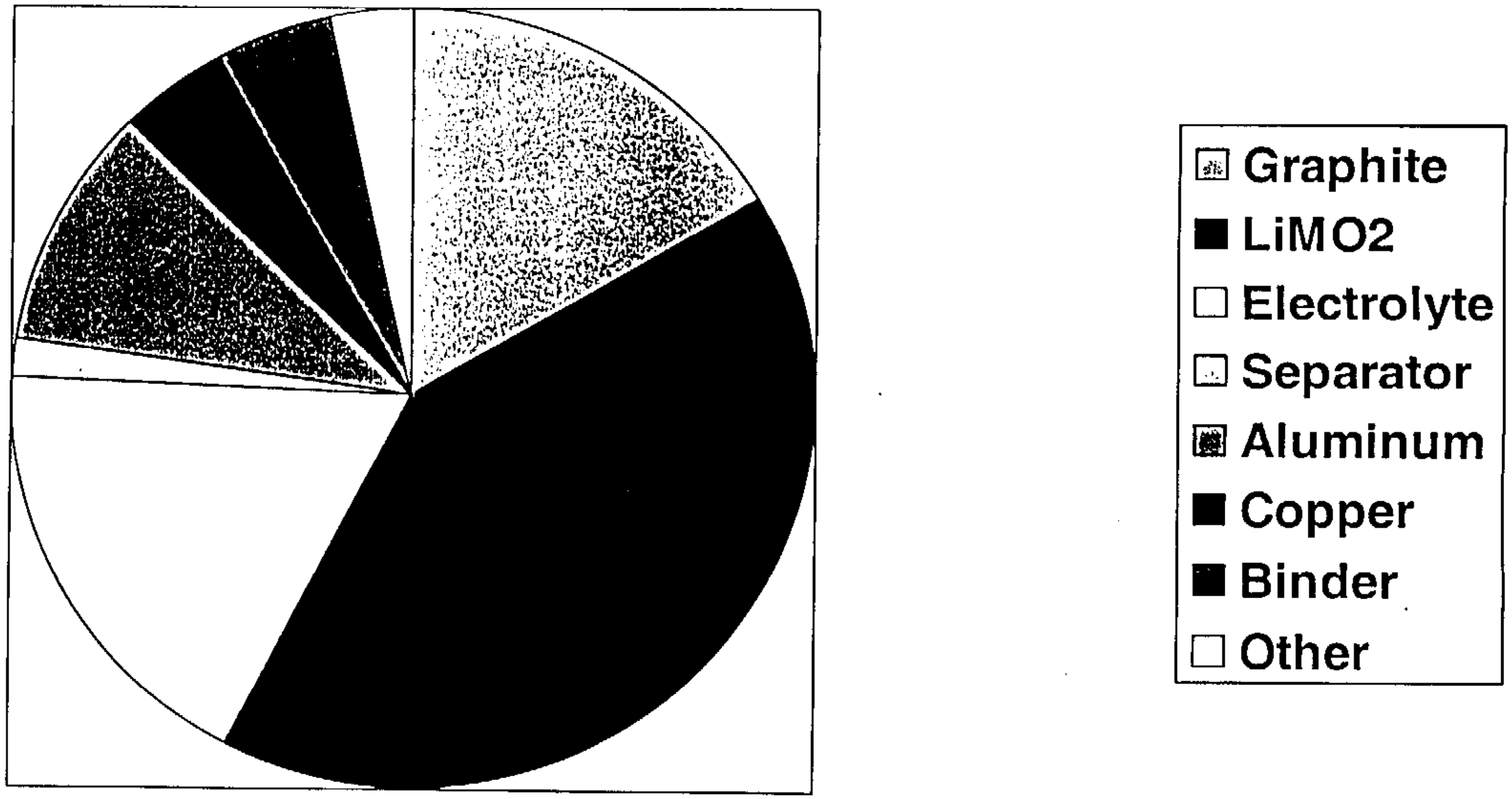
Current Status of Ni-MH Recycling

- Inmetco recycles Ni-MH batteries
  - pay for feedstock >30% Ni (~cell concentration)
  - plastic burned off
  - metals melted and refined
  - Ni and Fe recovered for use in stainless steel
    - ingots sold for ~90% LME price of contained Ni
    - large market will not saturate soon
  - MH elements to slag
    - low-value use as road aggregate

Ni-MH Materials to Target for Recycling

- Metal hydrides ~ 25 % material cost
  - currently recovered in low-value use
  - R&D on MH recycle clear priority
- Separator looks like another possible target
  - only makes sense if fabricated product recovered
  - unclear if that's possible
- Cobalt another candidate
- Should nickel be recovered as pure metal?
  - ~90% of its value already recovered
  - displaces virgin Ni in stainless manufacture
  - separate if another valuable component recoverable

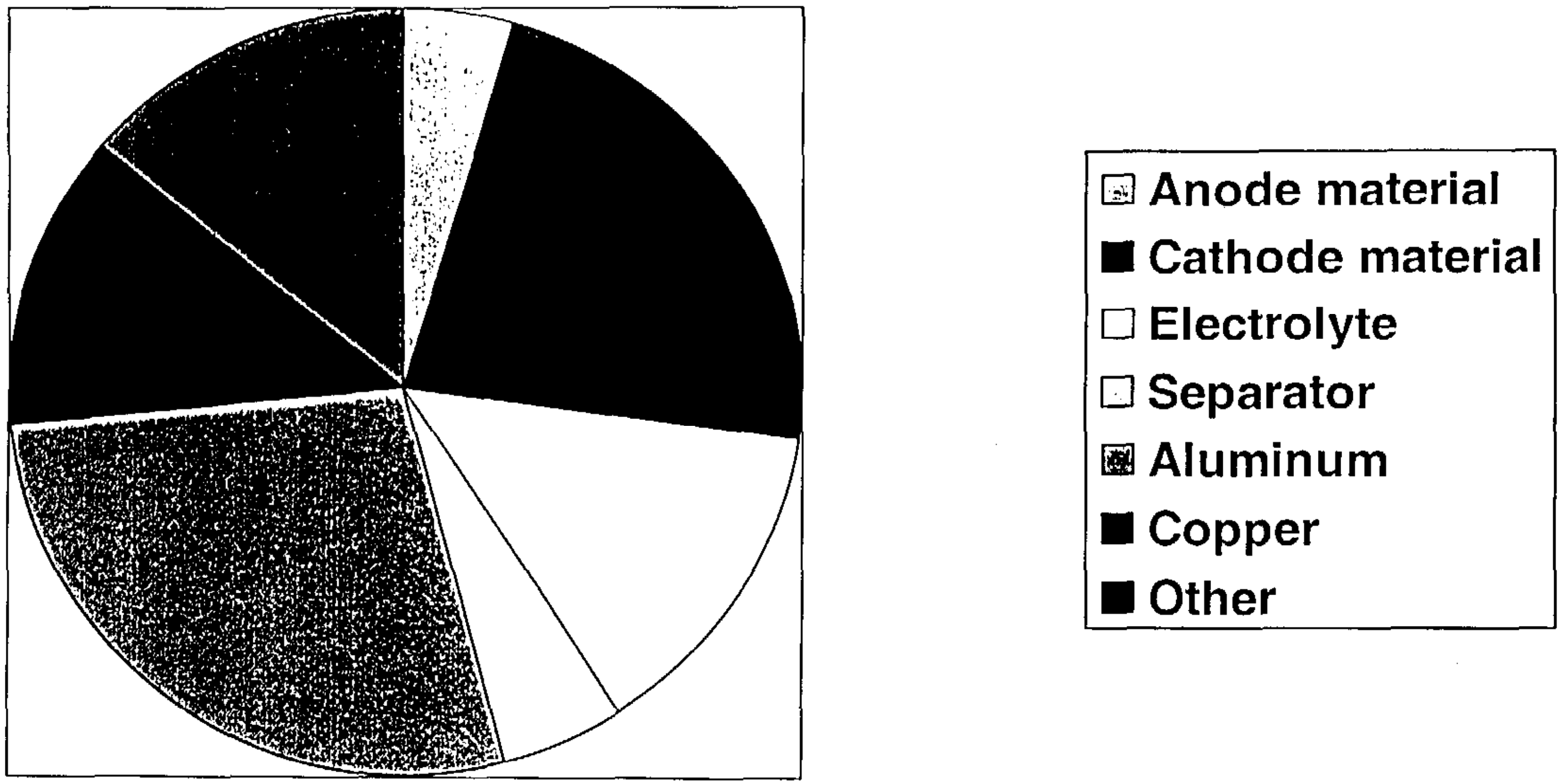
What's in a Li-ion EV Cell



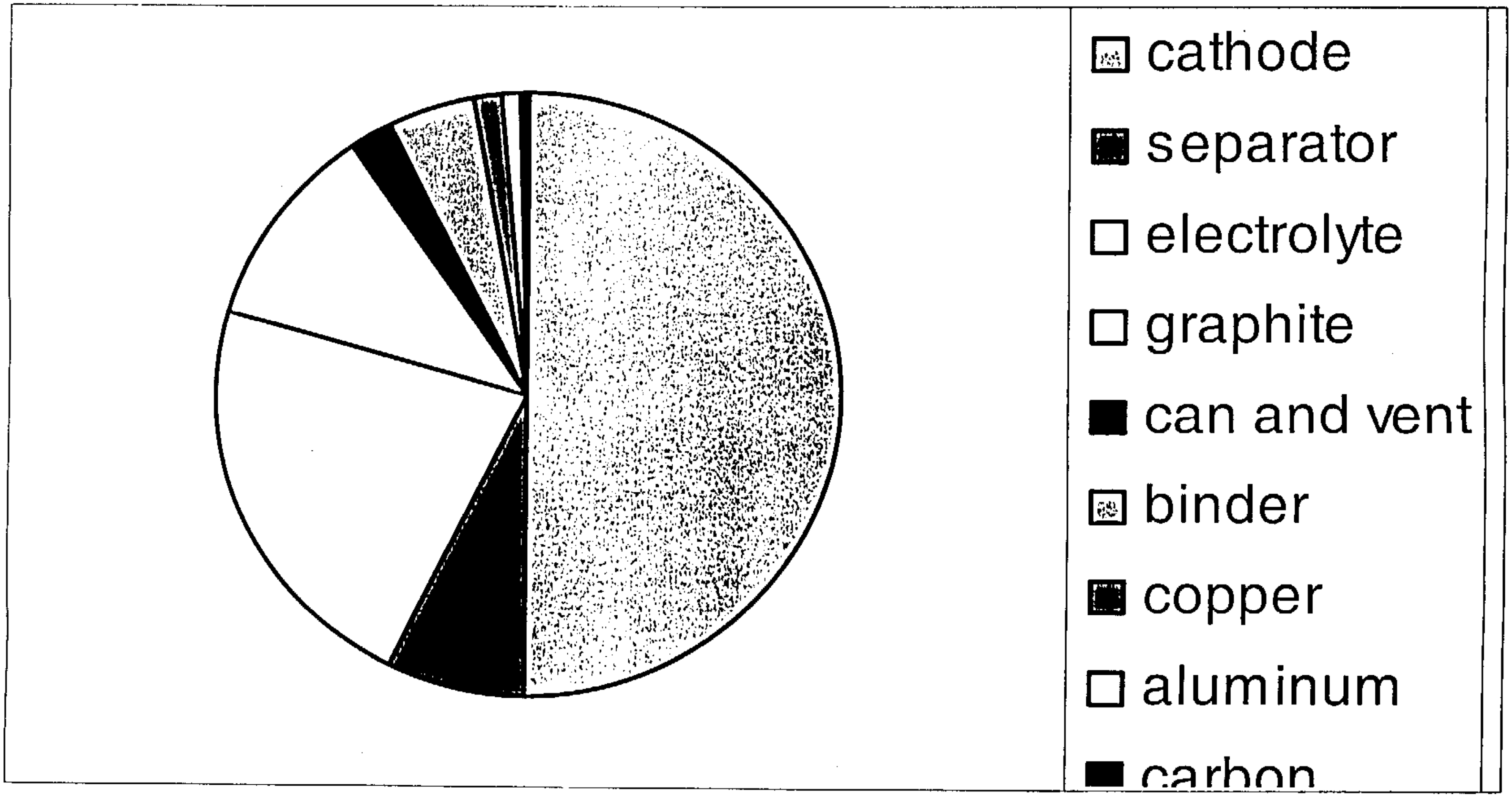
Li-Ion EV and HEV Battery Differences

- Same basic spiral-wound design
- Same materials
- HEV designs use thinner coating of electrode materials with more layers for high power
- Relative proportions and costs change (cathode less important)
- Requirements for cooling reduce cell size for high-power designs

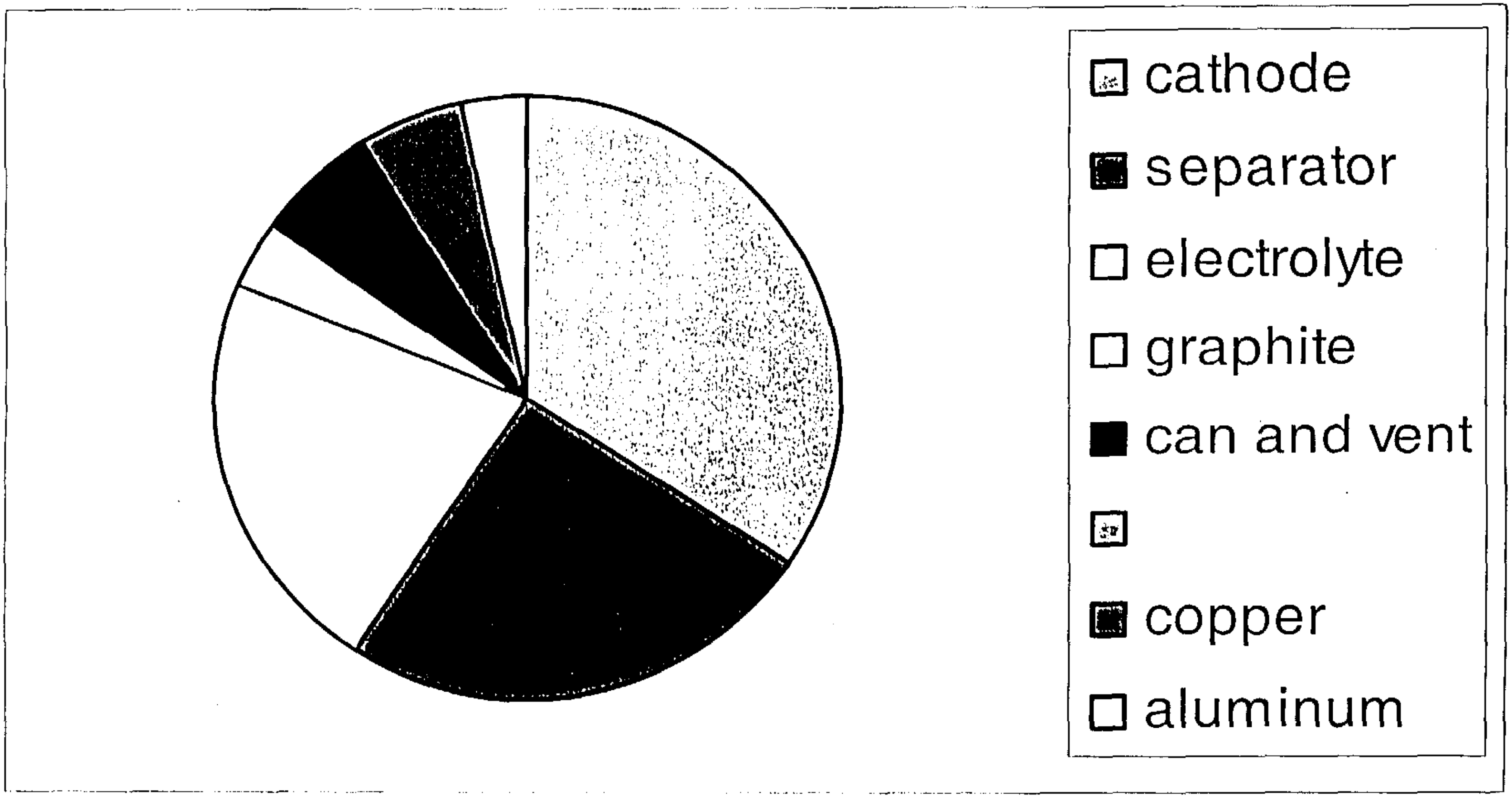
What's in a Li-Ion HEV Cell



Cost of Materials for Li-Ion EV Cell



Cost of Materials for Li-Ion HEV Cell



Li-Ion Materials to Target for Recycling

- Cathode remains main target even if cheaper material used
- Separator looks like target for HEV battery
- Electrolyte next obvious target
  - salt, e.g., $LiPF_6$ valuable component (\$~120/kg)
  - this is real opportunity
- Graphite could be considered for EV cells
  - unlikely because physical configuration must be retained

Separator Cost Mainly for Processing

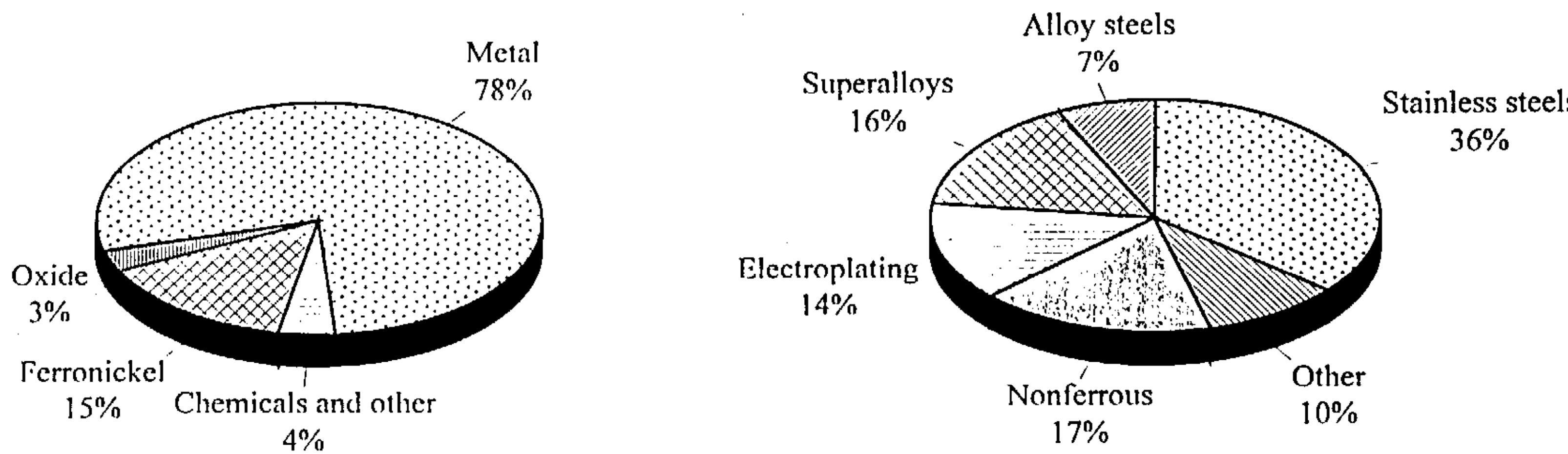
- Basic raw materials are polyethylene and polypropylene
  - Three 8-micron layers with 50% porosity
- Maximum price for pellets \$0.60/lb
- Processing to thin, porous film very costly
- Current price \$3-\$6/m^2 or \$120-\$240/kg
  - mass production goal \$1/m^2 or \$60/kg
- Recycling could only recover material value
  - under \$0.08/cell
  - would not pay

Current Status of Li-Ion Recycling

- Toxco and Sony recycle Li-ion batteries
- Toxco process is commercial
  - recycle large and small batteries
  - currently charge for service
  - processing cost ~$2/lb
  - revenues from Co recovery help defray cost
    - automotive batteries won't use (much) Co
  - economics will dictate recovery of other components
    - electrolyte salts can be recovered as well
    - need to convince users of quality of recycled product

Peter Kuck
U.S. Geological Survey

FIGURE 2
U.S. PRIMARY NICKEL CONSUMPTION BY FORM AND USE, IN 1998



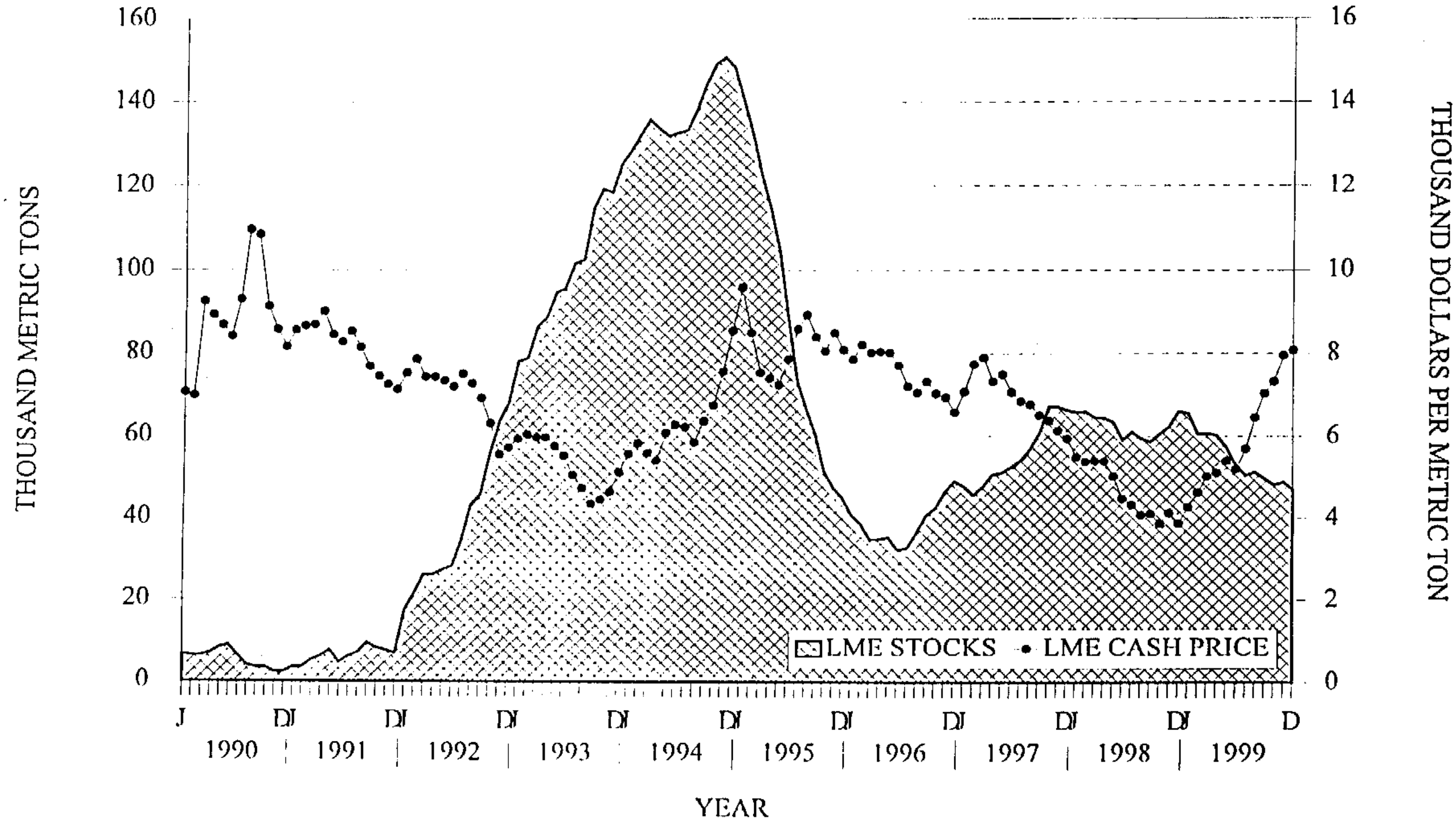
FORM

USE

PRIMARY CONSUMPTION: 116,000 METRIC TONS

FIGURE 1

NICKEL
LONDON METAL EXCHANGE CASH PRICE AND STOCKS



COBALT METAL vs. NICKEL METAL

PRICES - 1997 - 2000

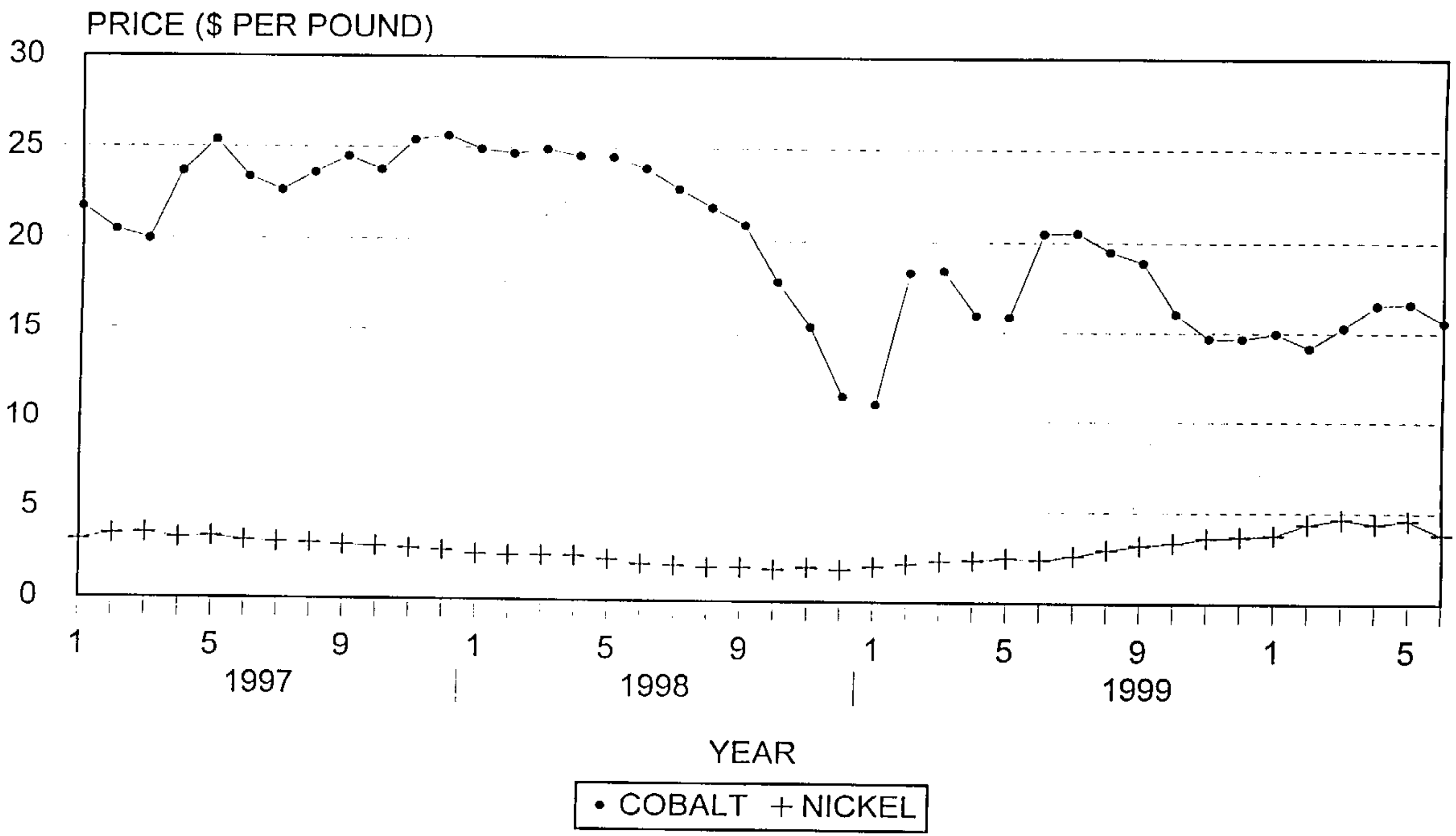
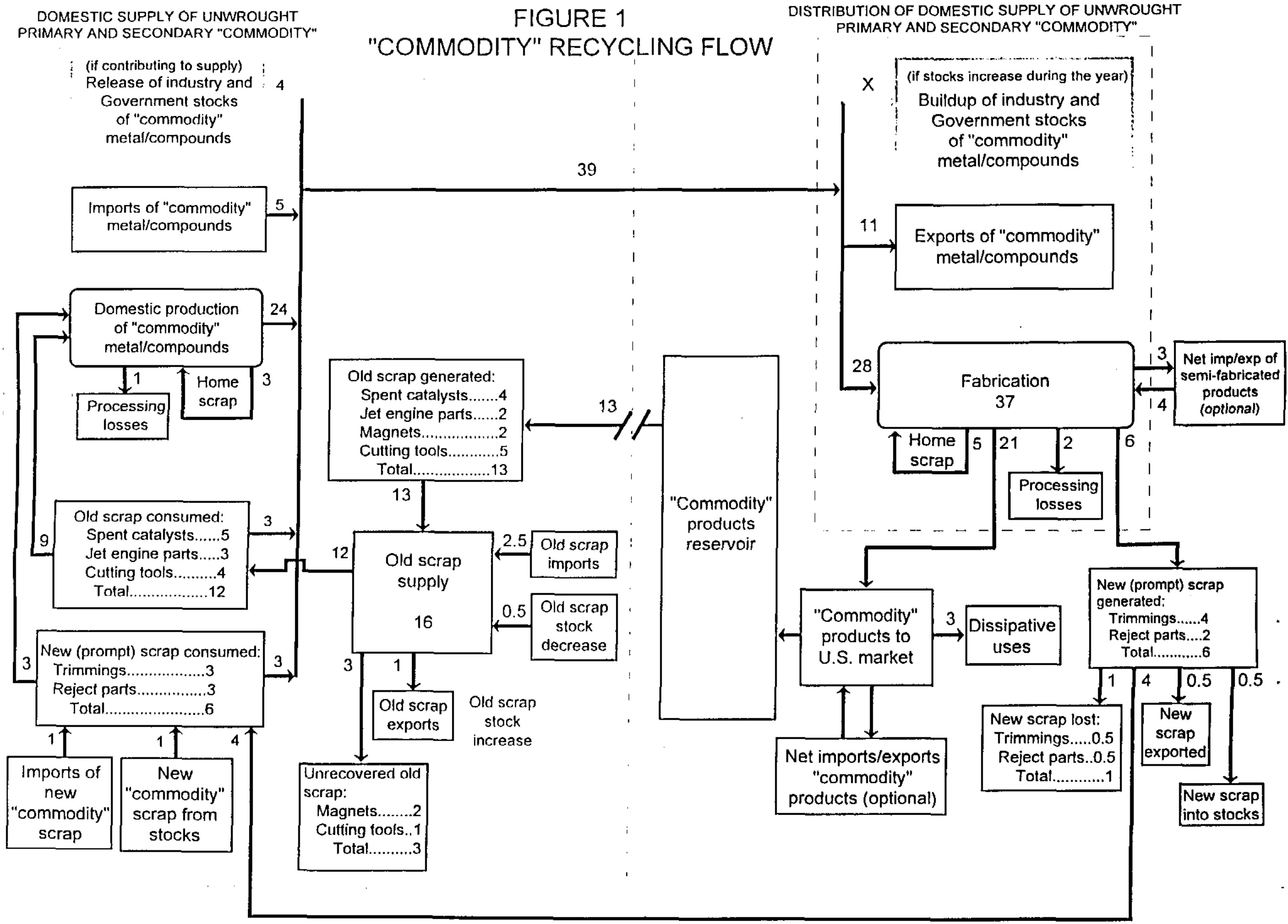
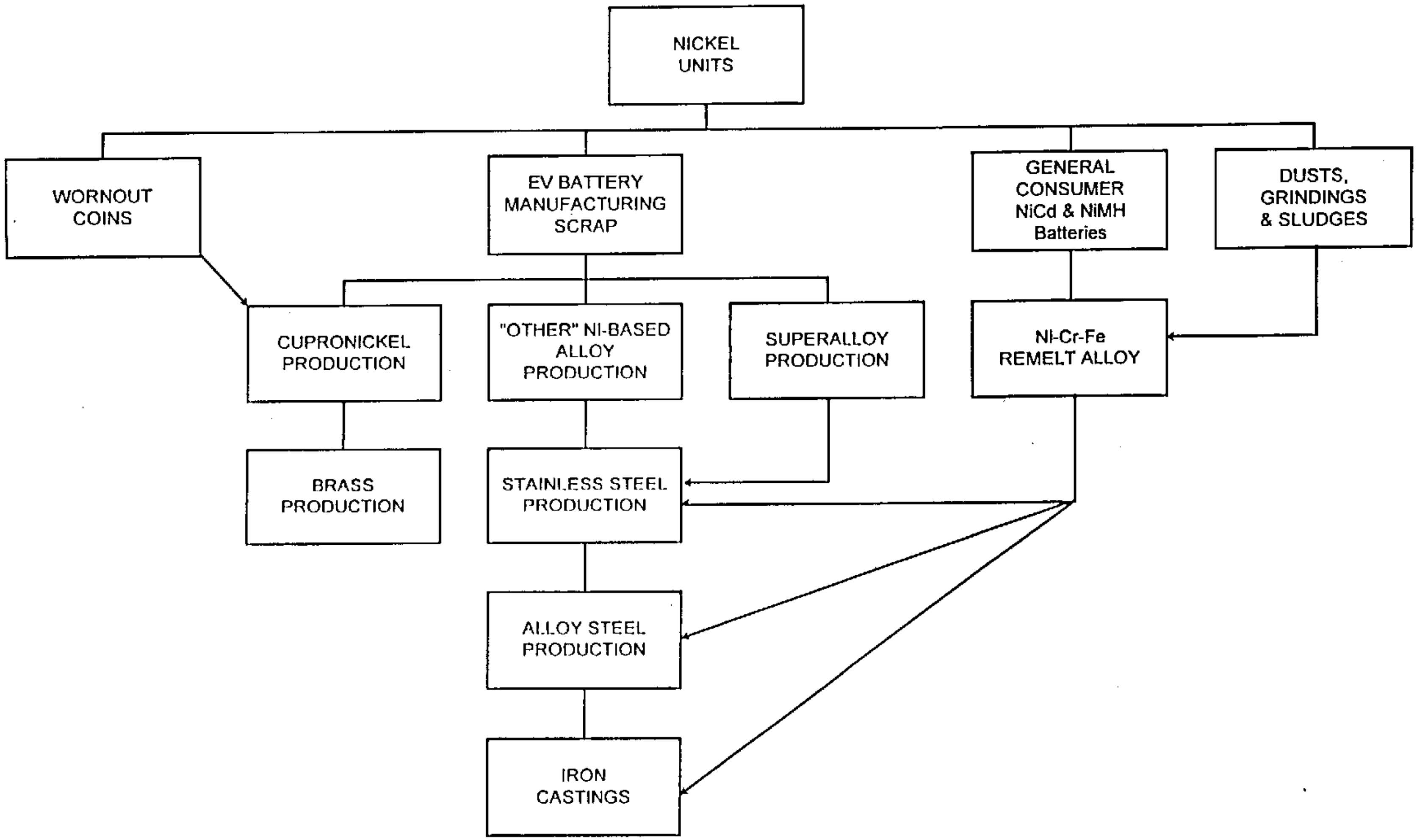


FIGURE 1
"COMMODITY" RECYCLING FLOW



DILUTION OF NICKEL SCRAP



Ken Money
INMETCO

INMETCO

Recycling to
Sustain Our Natural Resources

(Non-Battery) Secondary Materials Accepted at INMETCO for Recycling

- Flue Dust
- Swarf
- Cake
- Baghouse Dust
- Magnesium
- Spent Carbon
- Mill Scale
- Grindings
- Spent Acid
- Nickel Catalysts
- Chrome Catalysts
- Chrome Dust

INMETCO
Recycling to Sustain Our Natural Resources

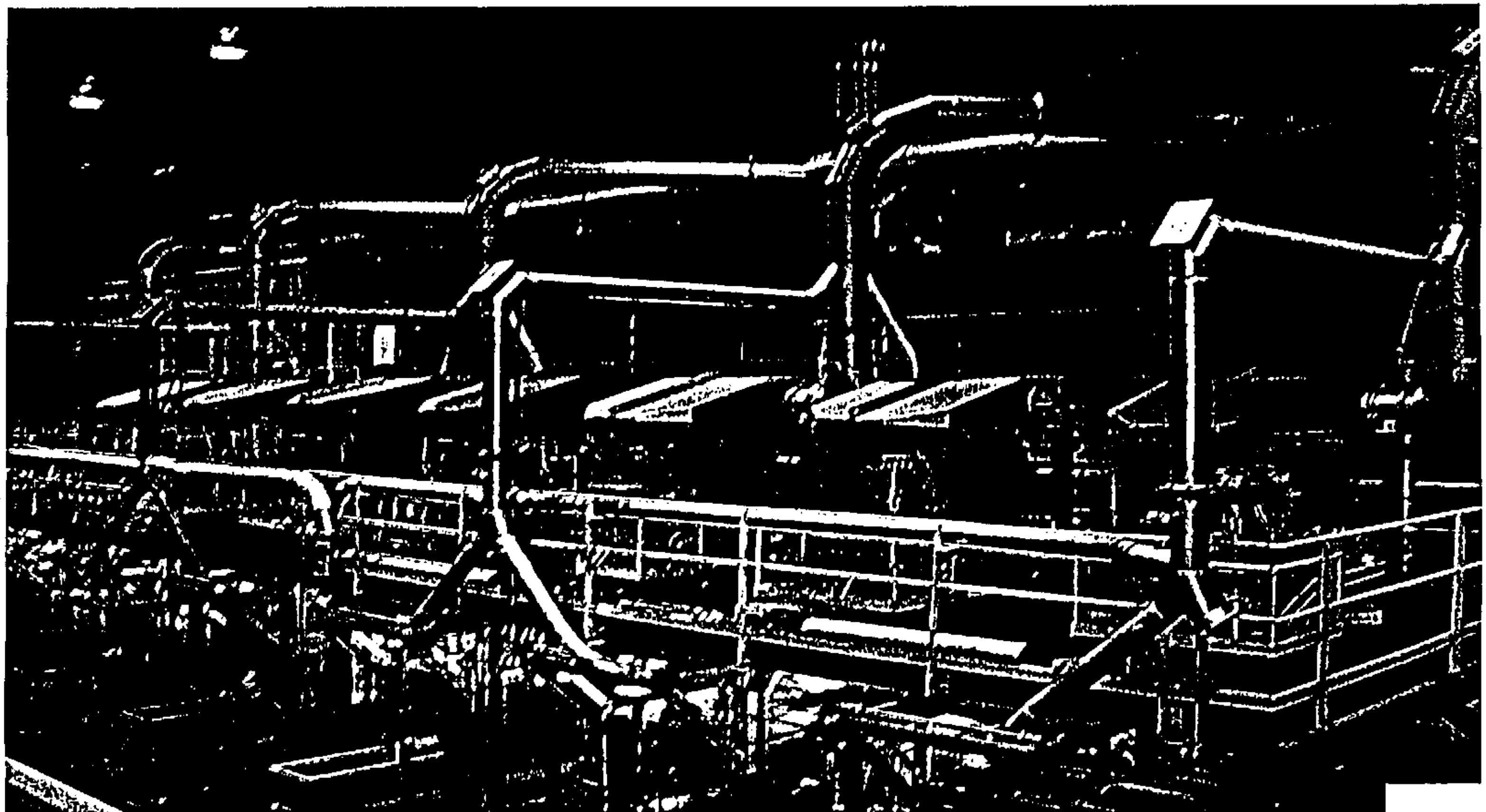
Spent Batteries Accepted at INMETCO for Recycling

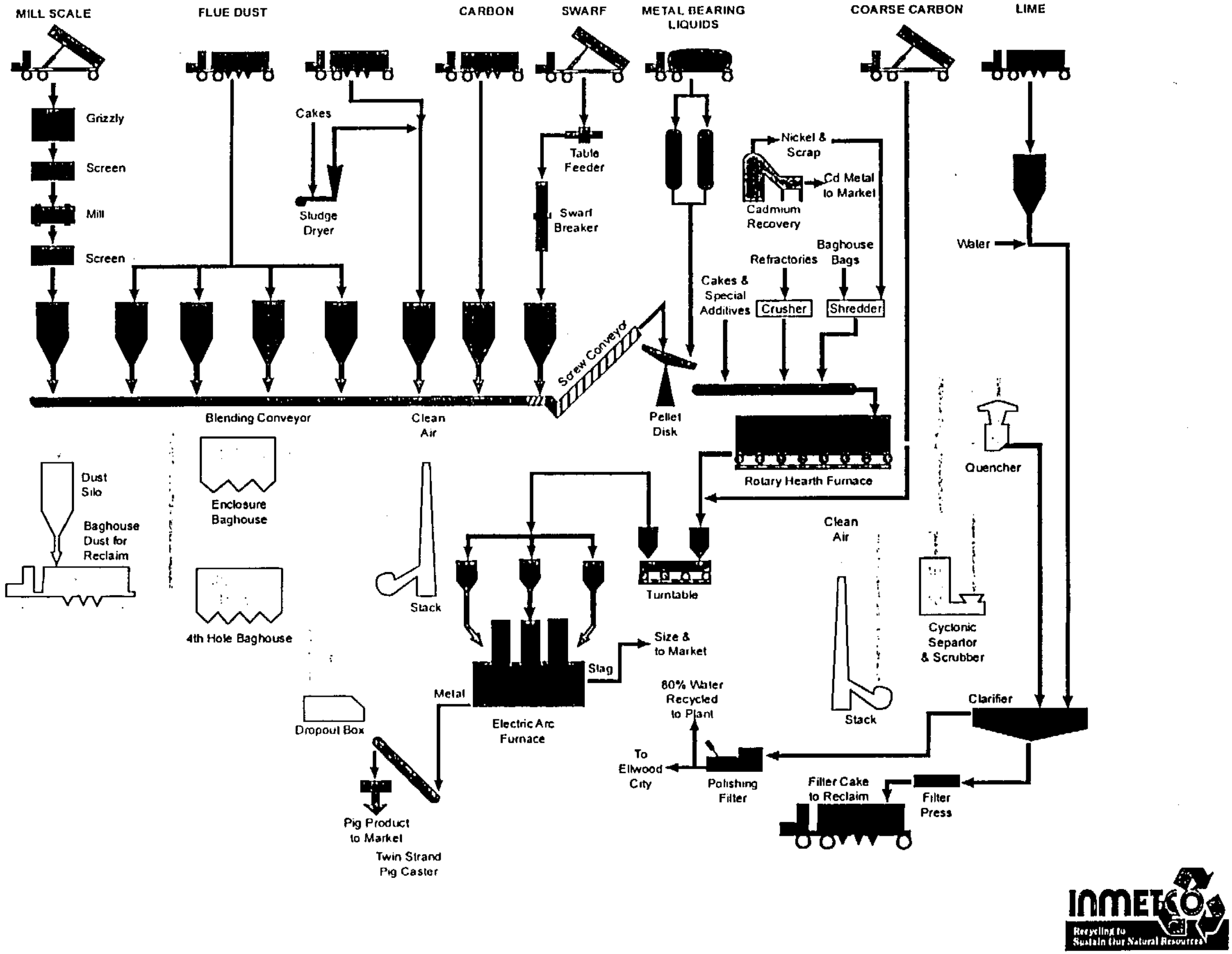
Nickel Cadmium
Nickel Metal Hydride
Lithium
Lithium Ion
Nickel Iron
Lead Acid
Nickel Zinc
Alkaline
Mercury
Zinc Carbon
Lead Carbonate
Zinc Carbonaire w/ Mercury
Nickel Copper
Zinc Carbonaire w/o Mercury
Magnesium
Sodium Nickel Chloride
Silver Oxide
Sodium Sulfur
Fuel Cells

Electric Vehicle Batteries

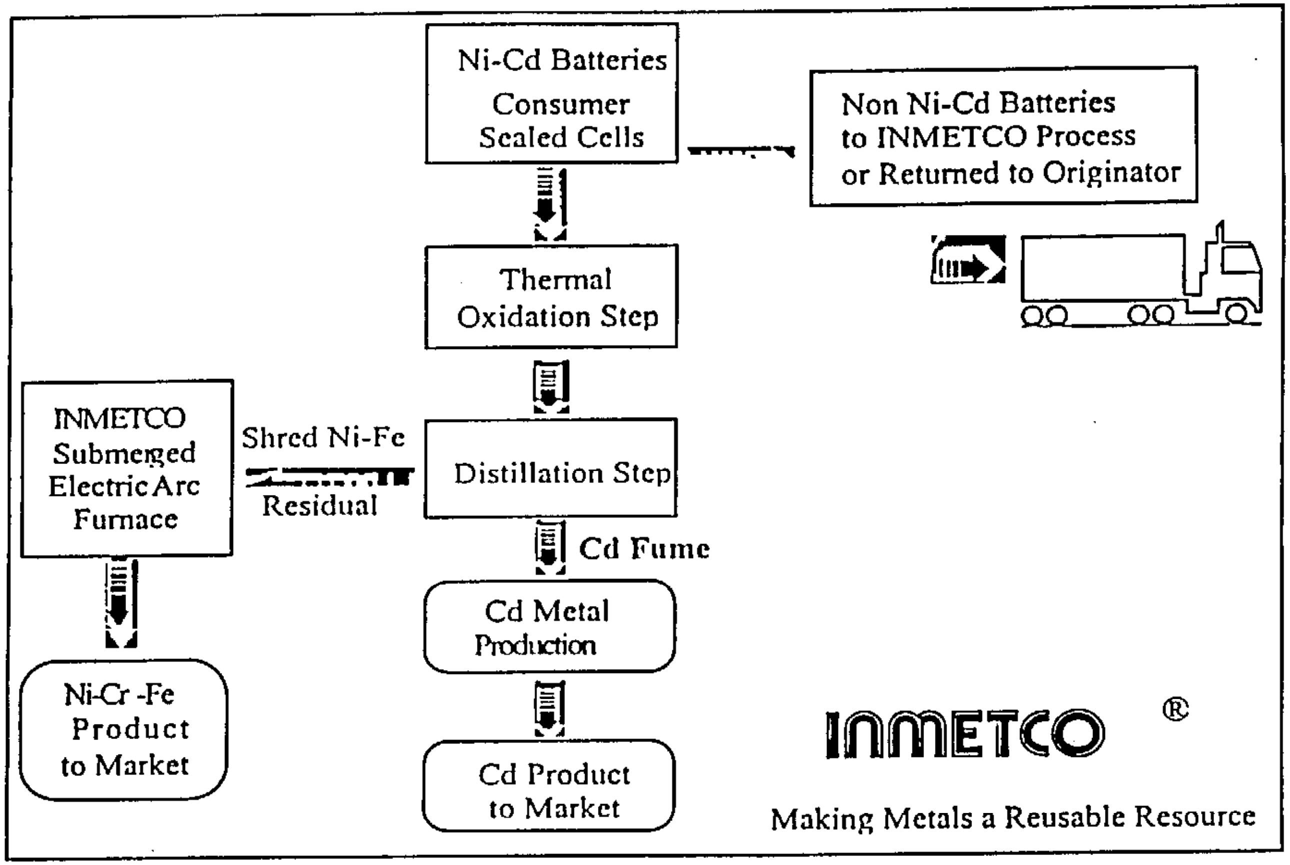
INMETCO
Recycling to Sustain Our Natural Resources

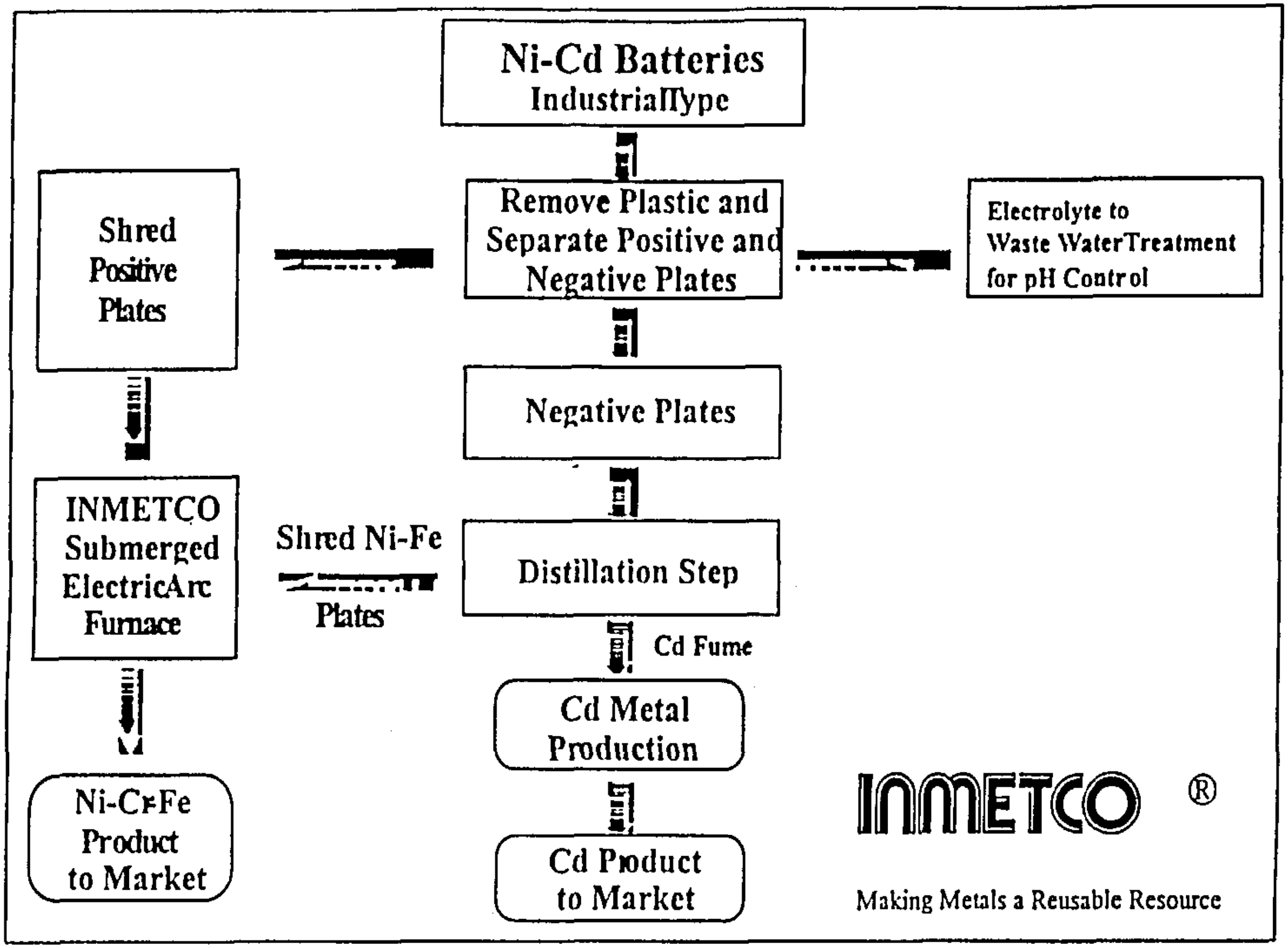
Inmetco's Cadmium Recovery Facility





MILL SCALE
FLUE DUST
CARBON
SWARF
METAL BEARING LIQUIDS
COARSE CARBON
LIME
Grizzly
Screen
Mill
Screen
Cakes
Sludge Dryer
Table Feeder
Swarf Breaker
Nickel & Scrap
Cd Metal to Market
Cadmium Recovery
Water
Baghouse Bags
Refractories
Cakes & Special Additives
Crusher
Shredder
Screw Conveyor
Blending Conveyor
Clean Air
Pellet Disk
Rotary Hearth Furnace
Quencher
Dust Silo
Baghouse Dust for Reclaim
Enclosure Baghouse
4th Hole Baghouse
Stack
Turntable
Clean Air
Cyclonic Separtor & Scrubber
Size & to Market
Slag
Metal
Electric Arc Furnace
80% Water Recycled to Plant
Stack
Clarifier
Dropout Box
To Ellwood City
Polishing Filter
Filter Cake to Reclaim
Filter Press
Pig Product to Market
Twin Strand Pig Caster
INMETCO
Recycling to Sustain Our Natural Resources


Ni-Cd Batteries
Consumer
Sealed Cells
Non Ni-Cd Batteries
to INMETCO Process
or Returned to Originator
Thermal
Oxidation Step
INMETCO
Submerged
Electric Arc
Furnace
Shred Ni-Fe
Residual
Distillation Step
Cd Fume
Cd Metal
Production
Ni-Cr -Fe
Product
to Market
Cd Product
to Market
INMETCO ®
Making Metals a Reusable Resource


Ni-Cd Batteries
IndustrialType
Remove Plastic and
Separate Positive and
Negative Plates
Shred
Positive
Plates
Electrolyte to
Waste WaterTreatment
for pH Control
Negative Plates
INMETCO
Submerged
ElectricArc
Furnace
Shred Ni-Fe
Plates
Distillation Step
Cd Fume
Cd Metal
Production
Ni-Cr-Fe
Product
to Market
Cd Product
to Market
INMETCO ®
Making Metals a Reusable Resource

Health, Safety, and Regulatory Issues to be Considered

- US-EPA Requirements
- State-DEP Requirements
- Universal Waste Rule
- OECD
- Basel Convention
- Hazardous vs Non-hazardous
- Employee and Community Safety

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Recycling to Sustain Our Natural Resources

Examples of OECD Countries that are Party to the Basel Convention

- Australia
- Germany
- Ireland
- Japan
- Spain
- United Kingdom

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Recycling to Sustain Our Natural Resources

Examples of Non-OECD Countries that are Party to the Basel Convention

- Brazil
- China
- Russia
- Singapore
- South Korea
- South Africa

INMETCO
Recycling to Sustain Our Natural Resources

Factors to Consider in Determining the Economic Feasibility of Battery Recycling

- Available Battery Volume
- Chemistry of the Battery to be recycled
- Revenue-generating materials from the battery to be recycled
- Value of the Product made from the recycled battery
- Potential problem elements to be dealt with
- Battery Chemistry Identification (Sorting)
- Costs
- Competition
- Customer Service (must make it easy for the customer to recycle)

INMETCO
Recycling to Sustain Our Natural Resources

Economic and Other Considerations Regarding Battery Recycling

- **External**
  - Customers
  - Products/Services
  - Geography
  - Potential Revenue Generation
  - Alternatives to Recycling
- **Internal**
  - Labor/Salaries/Assoc. Costs
  - Insurance
  - Taxes
  - Energy Requirement
  - Supplies
  - Services (Legal; Env; Mtce)
  - Equipment
  - Technology/Facilities
  - Permits
  - R & D Costs

INMETCO
Recycling to Sustain Our Natural Resources

Recycling Must be Easy for the Customer

- The recycler must have programs in place to make it easy for the customer to recycle the battery
- The costs must be acceptable to the customer
  - Recycling costs
  - Transportation costs
- The recycler must educate the customer about battery recycling
  - Battery types which can be recycled (ie, consumer cells vs industrial cells)
  - Battery chemistries which can be recycled
  - How to make it happen

INMETCO
Recycling to Sustain Our Natural Resources

Joseph Kejha
Lithium Technology Corporation

The Development of a Process for the Recycling of Lithium from Lithium Battery Waste

Steven Tyrrell

Prof. Barry Welch

Dr. Rudolf Steiner

Dr. Paul Pickering

The University of Auckland

PACIFIC LITHIUM LIMITE

Outline

- Lithium Batteries
- Battery Recycling
- Electrolytic Lithium Recovery
- Energy Reduction
- Closing the Loop

Spent Battery Processing

Remove wrappers & packaging

Frozen in liquid N_2

Cut up & shredded

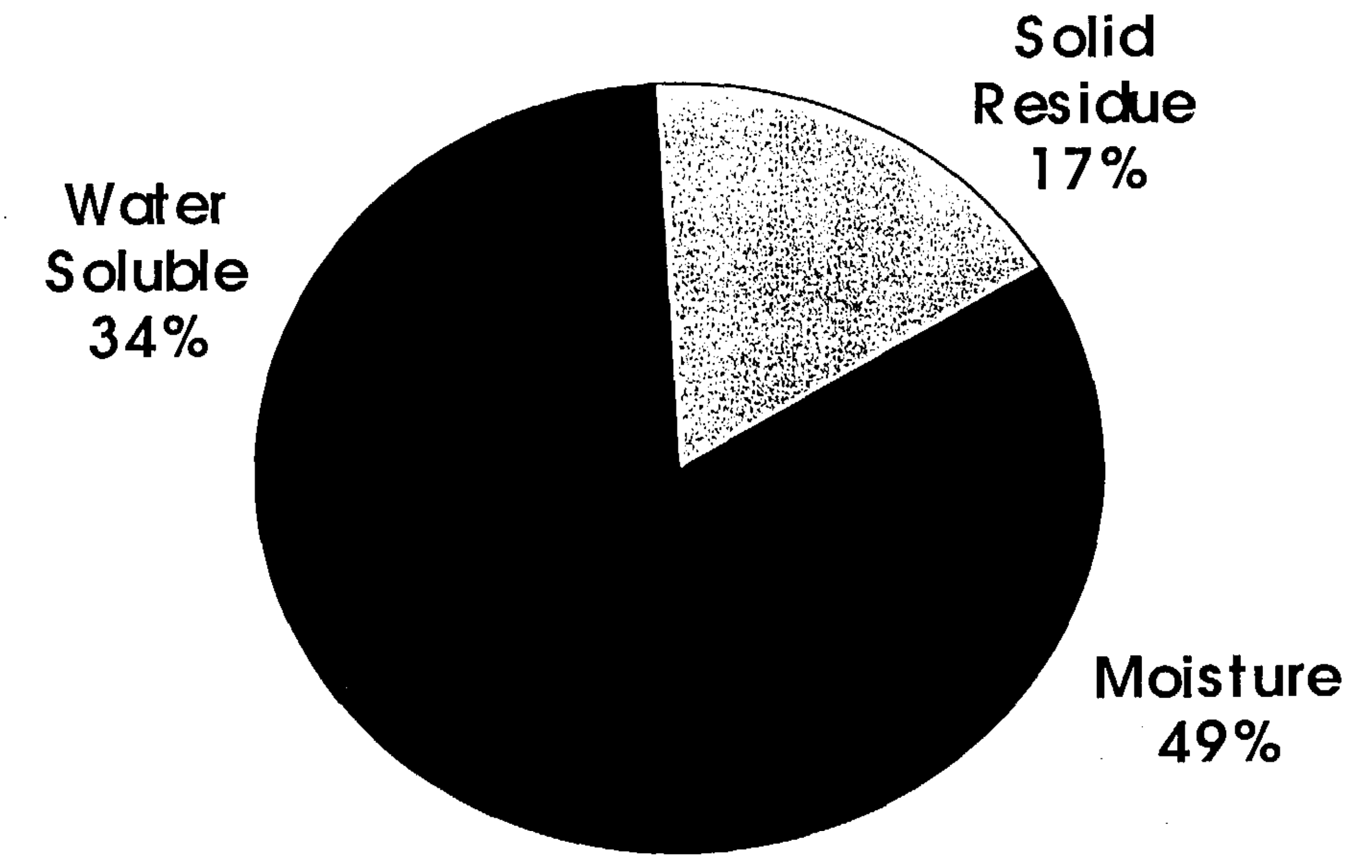
Reaction with aqueous LiOH

Solids filtered & dewatered

Packed & shipped

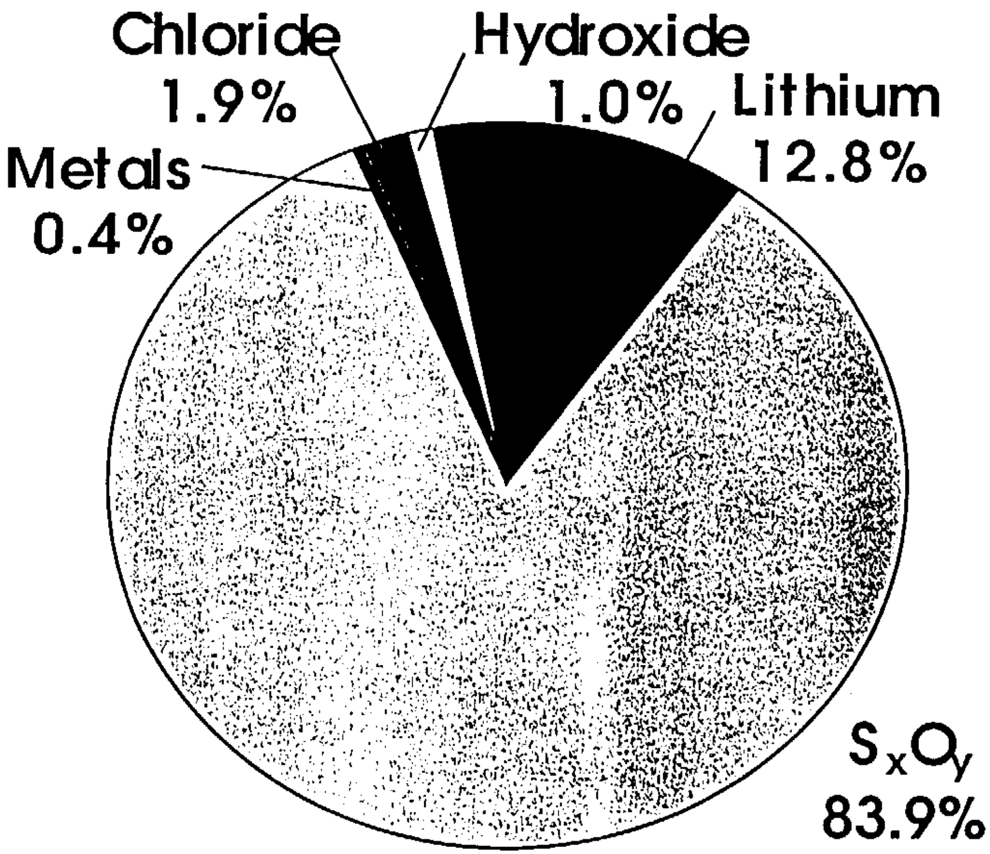
Waste Characterisation

Composition by Weight

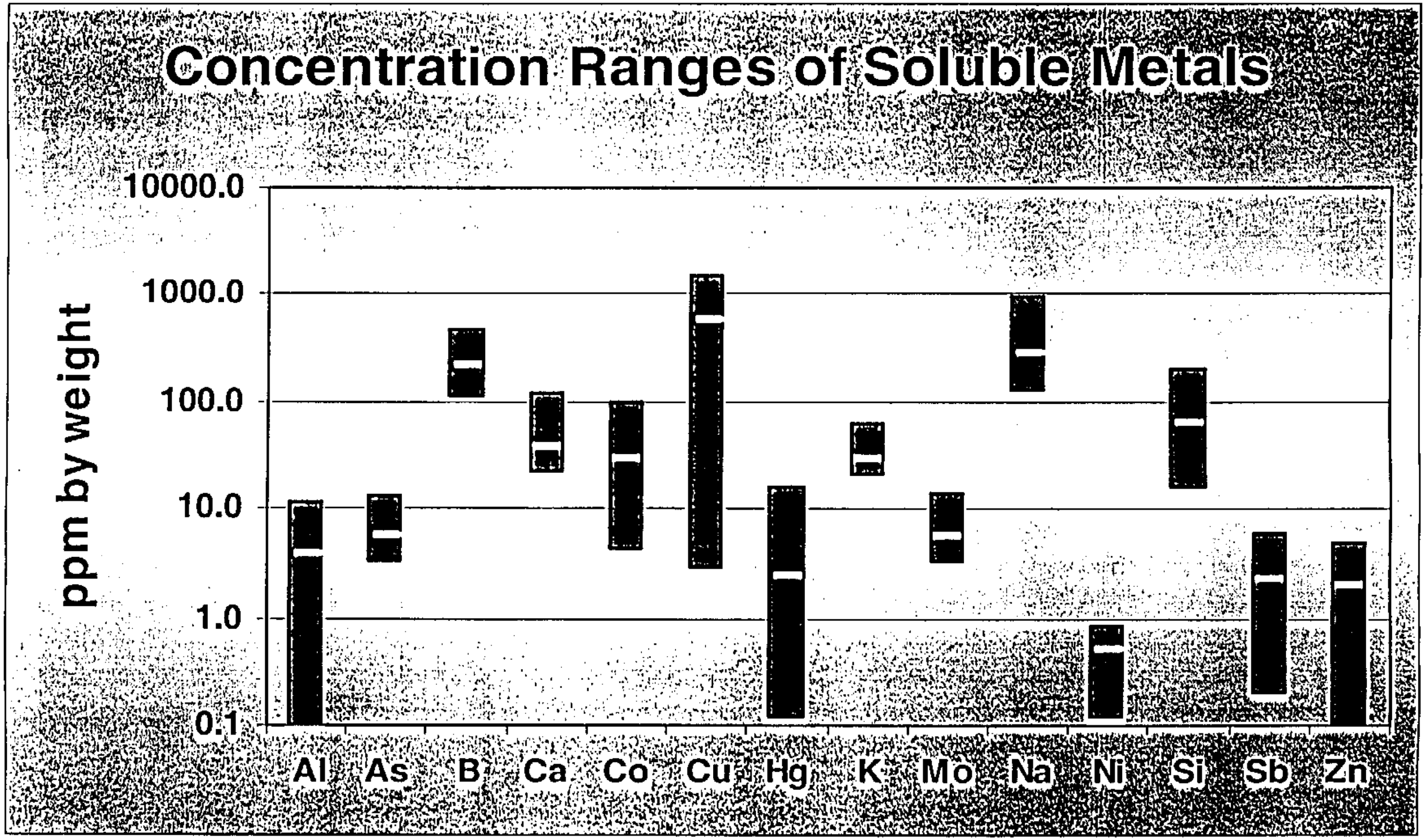


Waste Characterisation

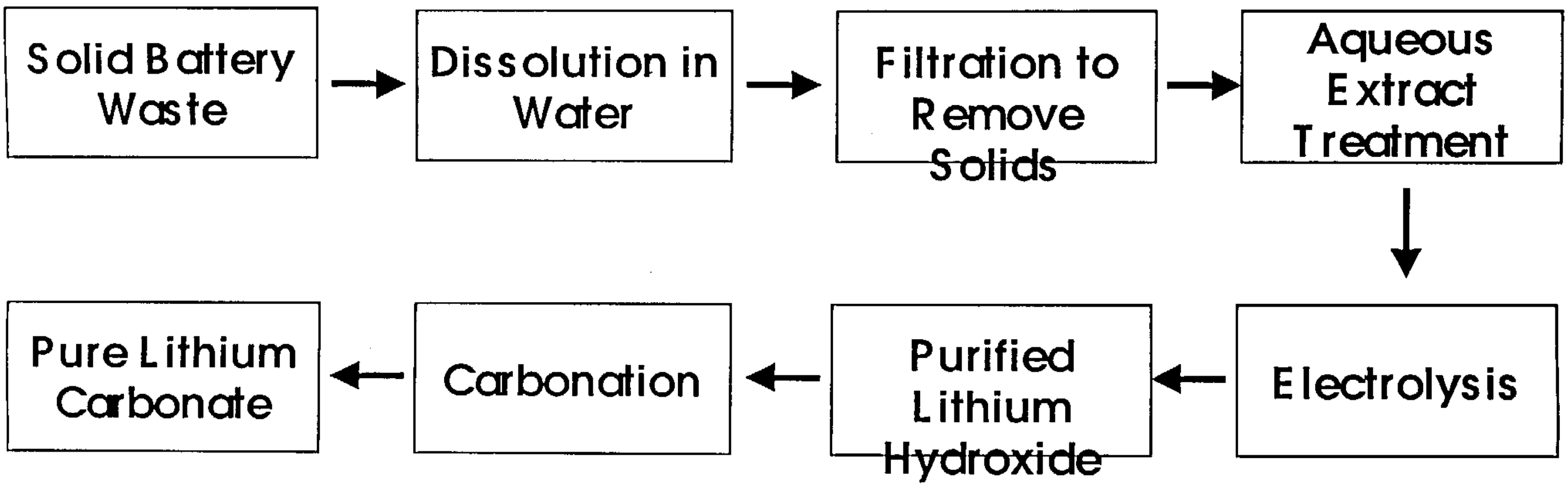
Water Soluble Material



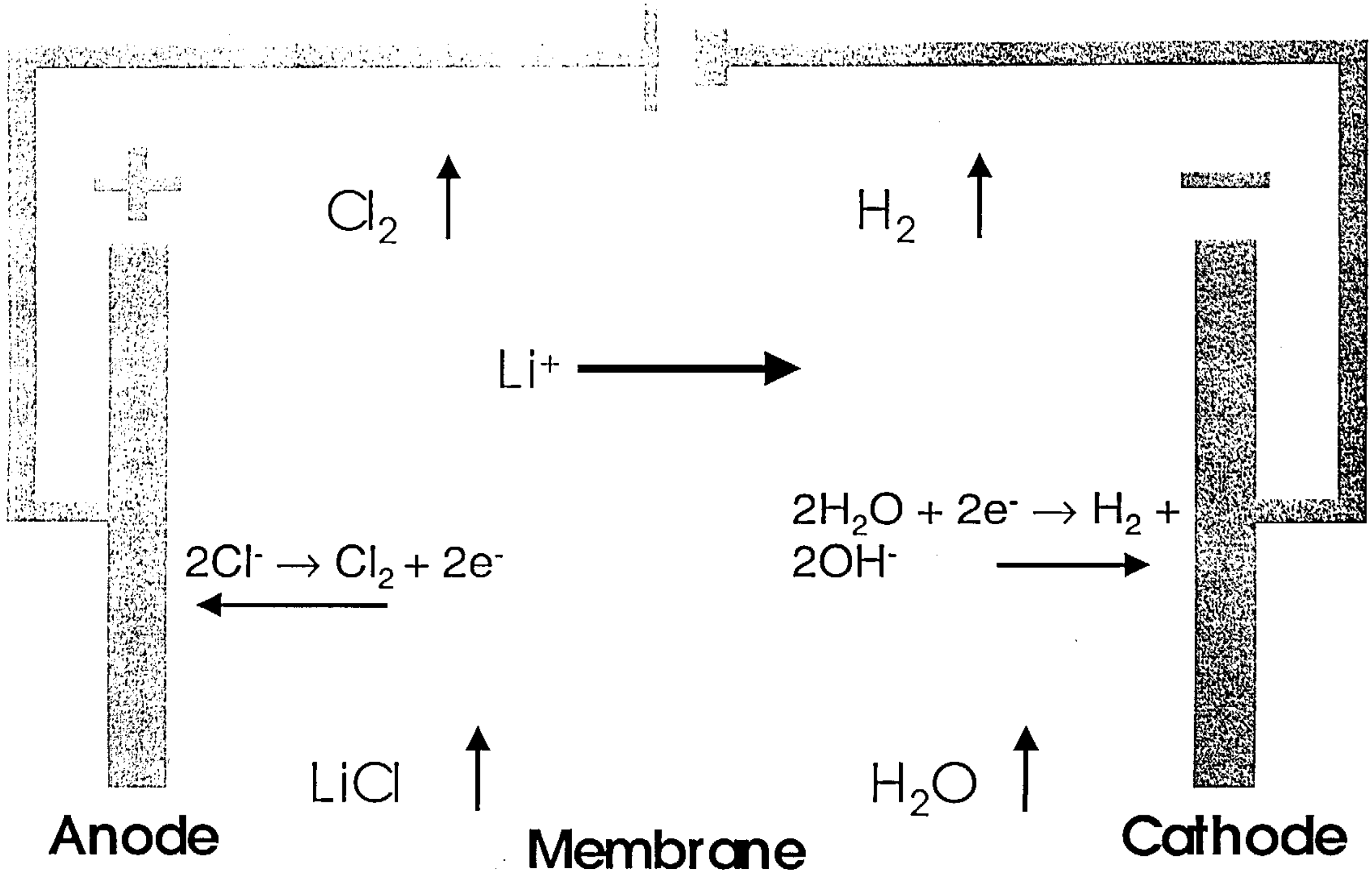
Waste Characterisation



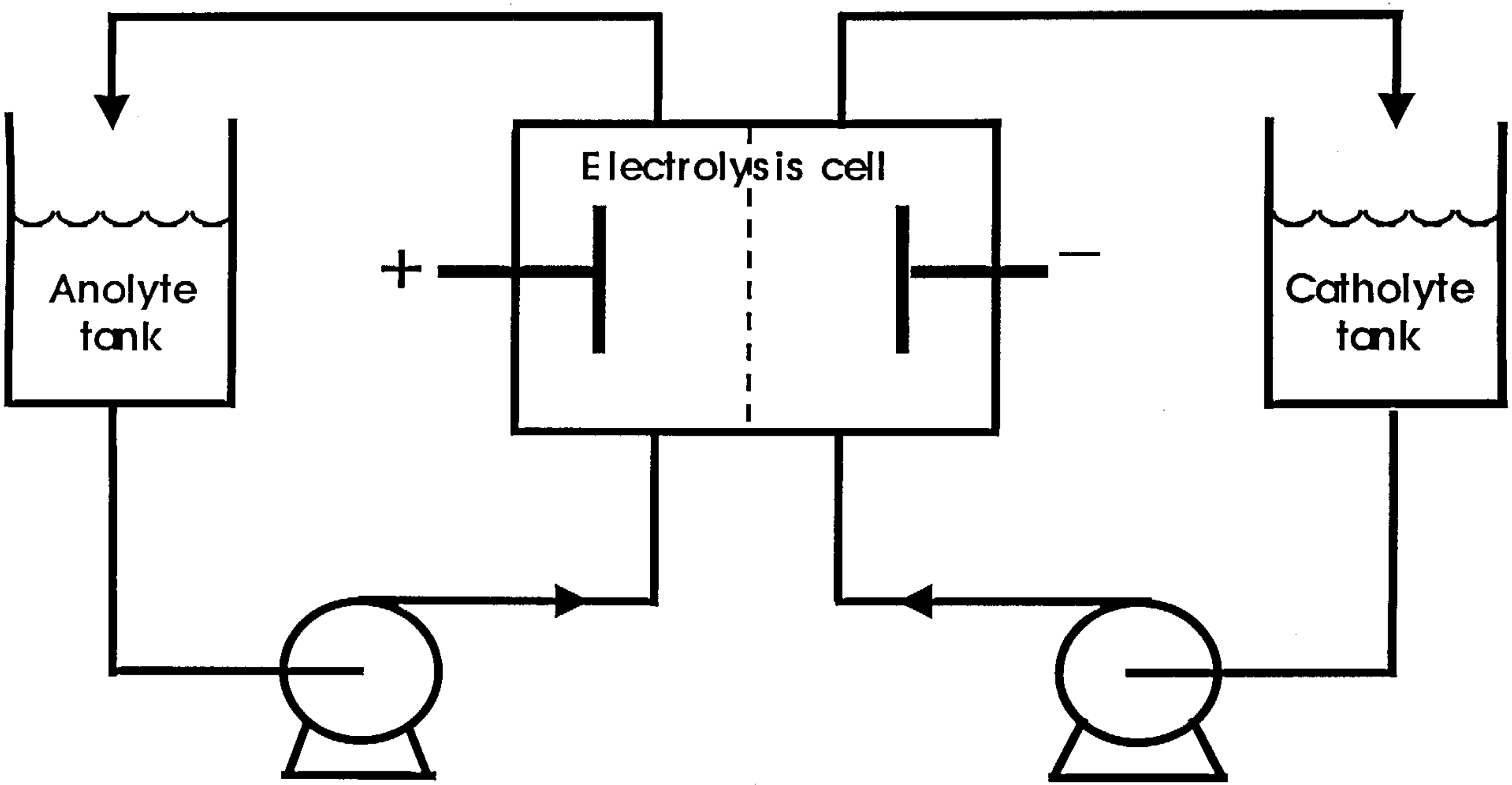
Li Recycling Process



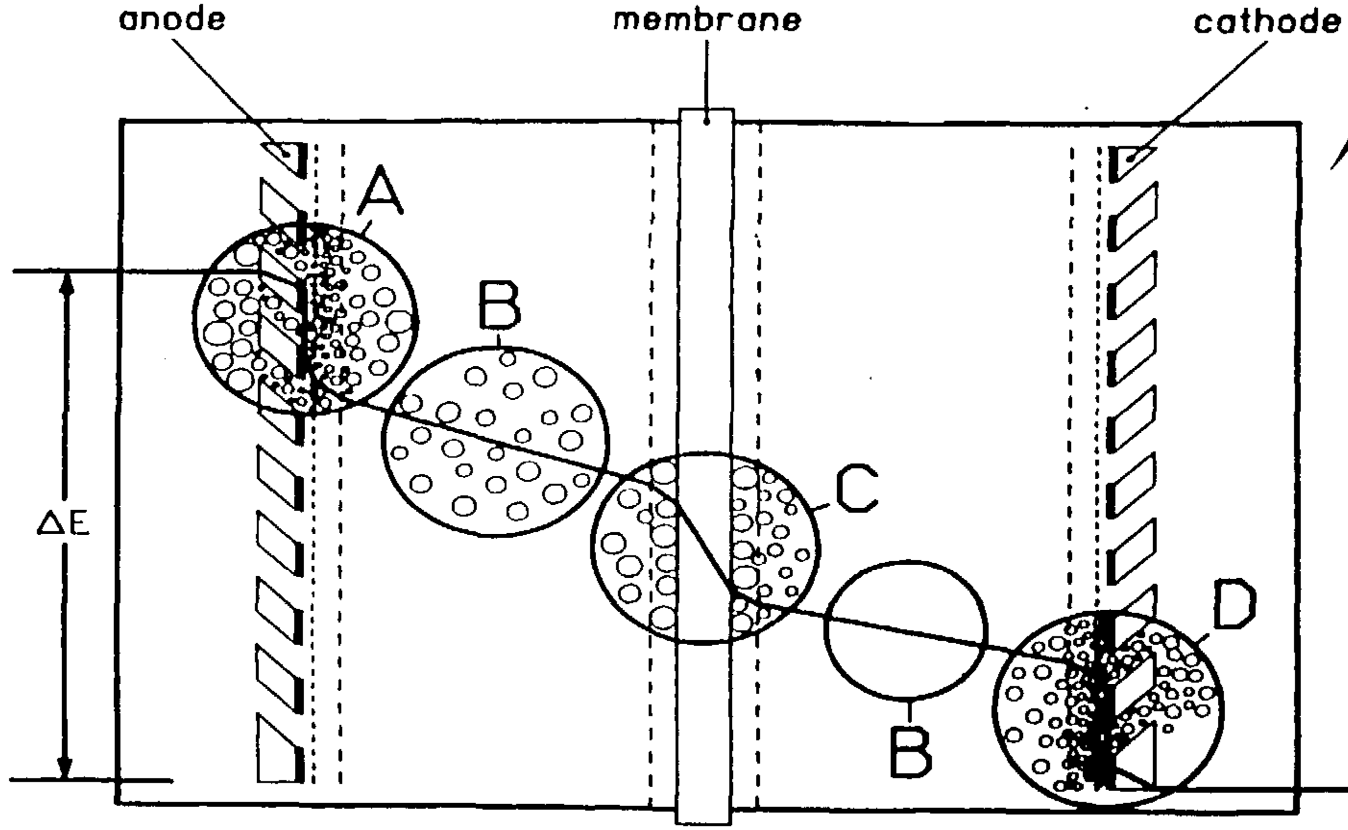
Membrane Electrolysis Cell



Experimental Setup



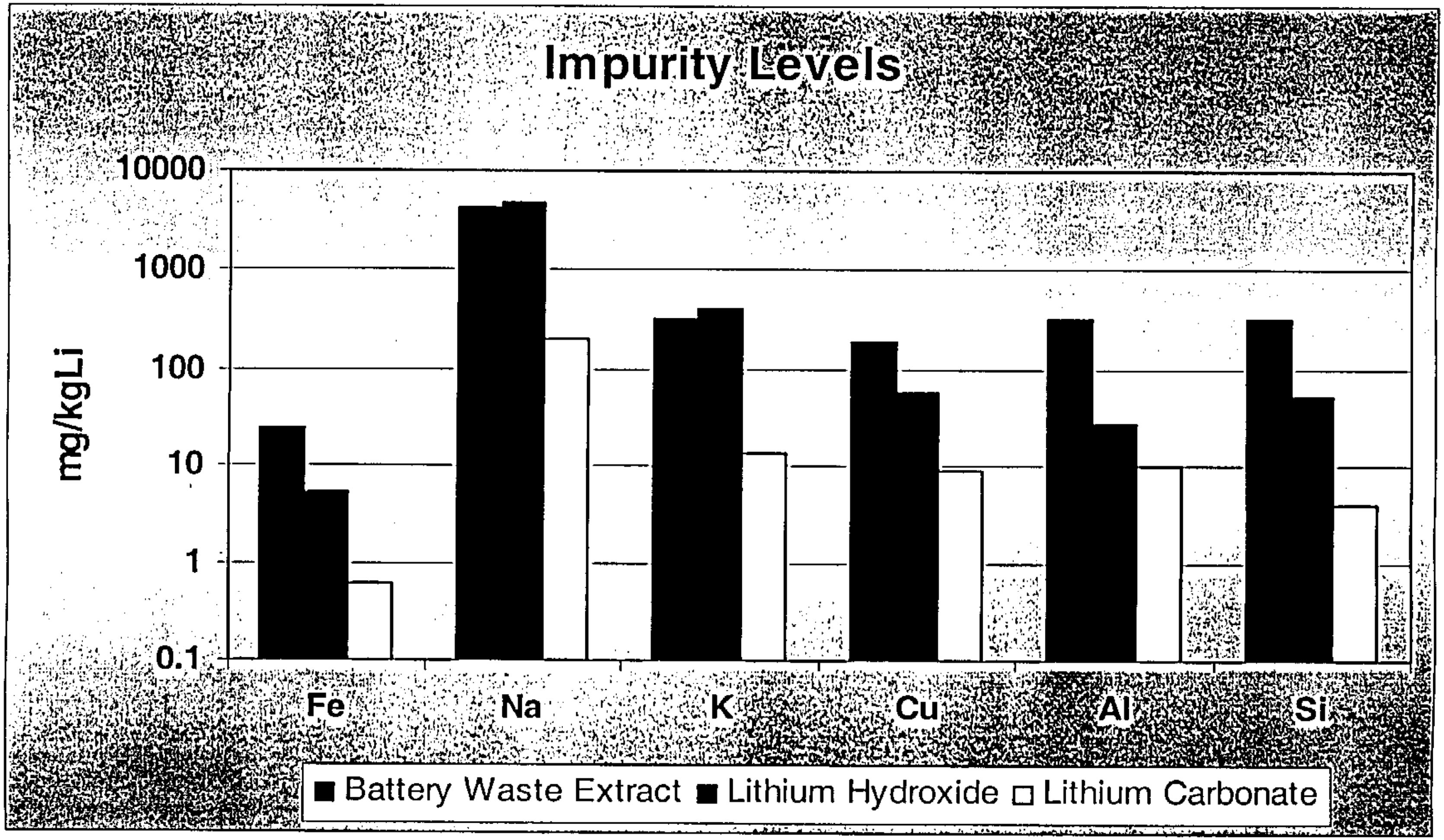
Energy Consumption



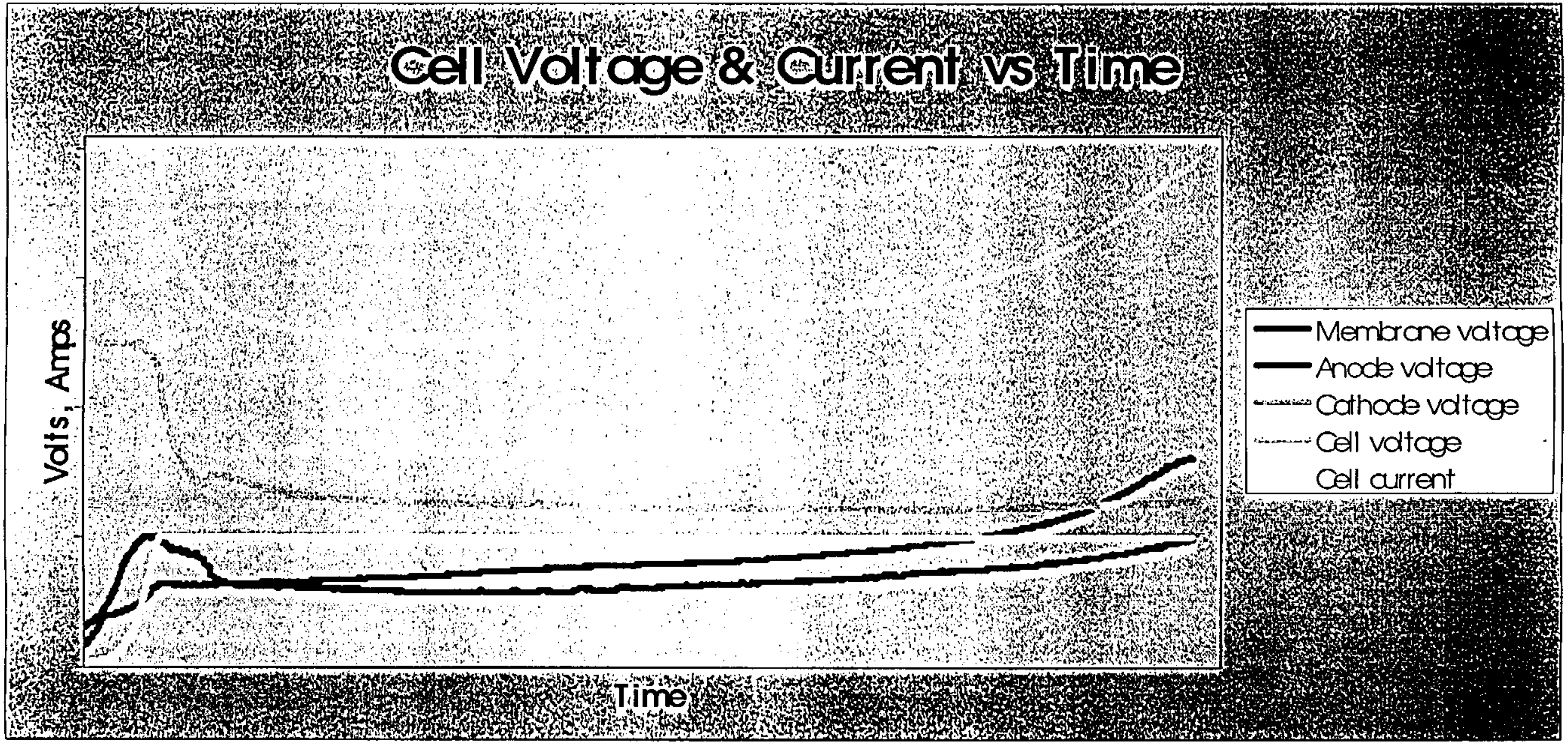
Source: R.E.White, Electrochemical Cell Design

$$E_{cell} = iR^{A}{}_{circuit} + (E^{A}{}_{e} + \eta_{A}) + iR_{anolyte} + iR_{membrane} + iR_{catholyte} + (E^{C}{}_{e} + \eta_{C}) + iR^{C}{}_{circuit}$$

Membrane Performance



Cell Dynamics



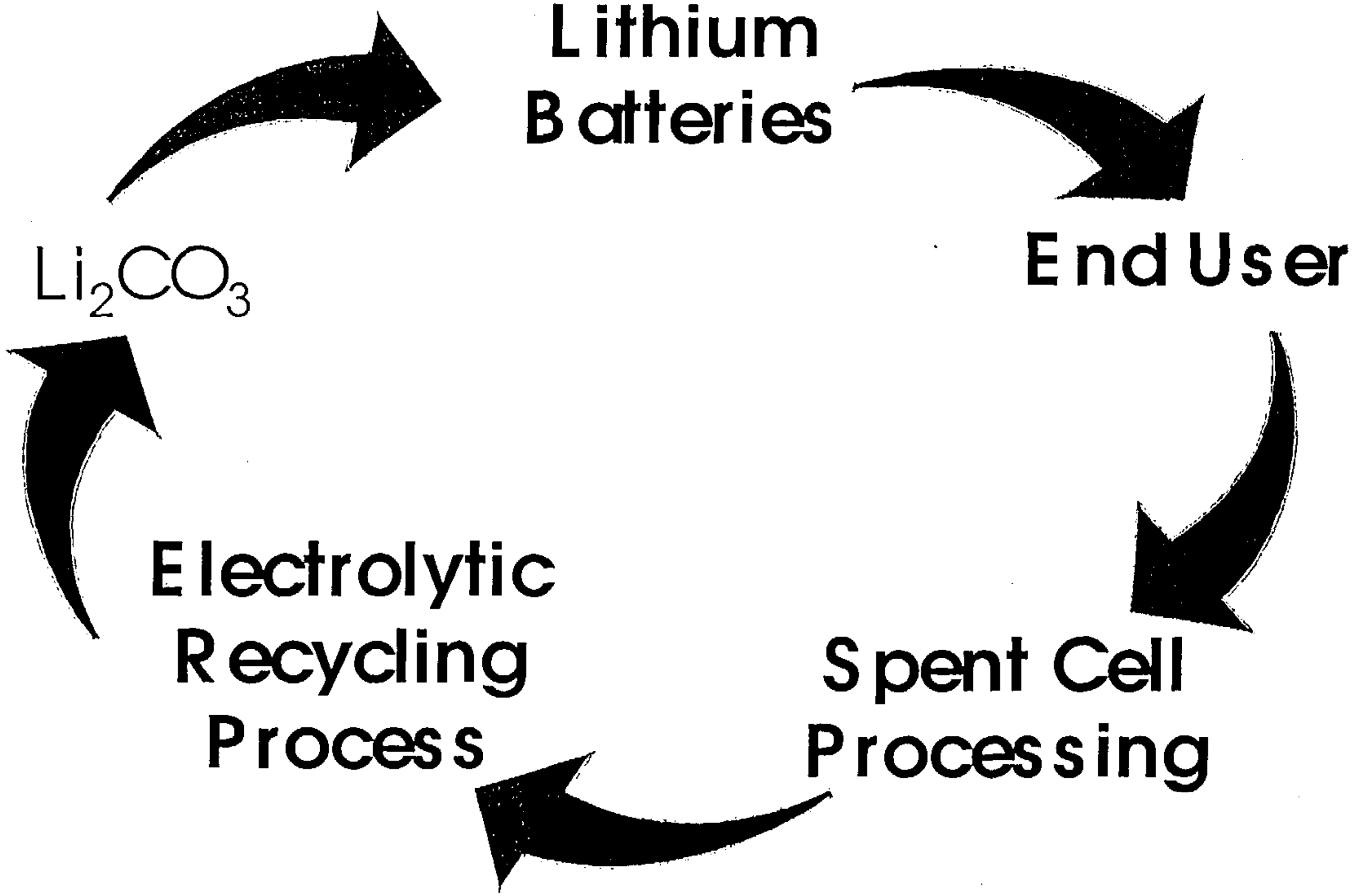
Conclusions

- Recovery of lithium possible at high current efficiencies
- Stable electrode materials with low overvoltage selected
- Membrane with low voltage drop and high current efficiency selected

Conclusions

- Further electrode and membrane performance studies required
- Investigate cell design options for low energy consumption
- Recovery of other materials from lithium battery by-products

Closing the Loop



Acknowledgements

Technology New Zealand

University of Auckland Technical Staff

Pacific Lithium Ltd. Laboratory Staff

DuPont Nafion

Paul Gifford
GM Ovonic

RURAL ELECTRIFICATION
MEXICAN PROJECT

GM Ovonic

- **Opportunity to sell batteries in a second application after use in EV**
  - End of life batteries would be scrapped otherwise
  - Scrapping represents a low revenue alternative ($ 12/ea.)
  - Envision $ 50 to $ 150 kw/h in second use
  - Critical program for Mexican government
  - Rural electrification deficit growing
  - Environmental aspect is a major opportunity
  - Same scenario applies to C.A. and S. America
  - Other potential opportunities for other secondary applications i.e. communications, oil industry, etc.

RURAL ELECTRIFICATION MEXICAN PROJECT

GM Ovonic

- **Today's facts:**
  - Mexican population - 93 million
  - Rural population - 24 million
  - Unattended population - 5 million (1 mill. families)
    - Non-electrified villages - 85,000
- **Barriers to electrification**
  - High population dispersion
  - Difficult terrain conditions
  - Increasing costs
- **Memo:**
  - 2.0 billion (40%) people worldwide without electricity

RURAL ELECTRIFICATION MEXICAN PROJECT

GM Ovonic

- **Electrification Statistics:**
  - Existing solar home systems - 40,000
  - Electrified communities - 1300
  - Poulation served - 200,000
    - Non-electrified villages - 85,000
    - Communal buildings - 917
    - Health clinics - 700
    - Rural telephones - 12,000
- **Expected growth for 1999 & 2000:**
  - Projected current deficit - 2.5 million people
  - Replacement for existing systems - 20,000
  - New solar home systems - 60,000
  - Private sector new systems - 10,000
  - (90,000 systems = 3,500 packs)

RURAL ELECTRIFICATION MEXICAN PROJECT

- **What is being done:**

  - Batch of remote power systems (batteries & solar panels) being tested at the lab and at Pilot Community
  - Currently (3/13-15) evaluating business case on a joint basis with the State of Oaxaca
  - First data system recollection being obtained
  - Studying most efficient manner to provide infrastructure
    - Systems set-up
    - Replacements
    - Self-sustained community concept
  - High level of interest from other states in Mexico
  - Evaluating different funding options

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Ni/MH Battery Recycling Issues

- Most manufacturing and R&D scrap is being sent to INMETCO
- Very few batteries have as yet been returned from the field
- Small lots of material don't interest commercial smelting operations
- Waste generators are forced to give material away
- Turmoil in metals markets and falling prices due to foreign dumping further lessen demand
- Small battery market is also soft, adding to the problem
- Some concern regarding volatility of negative electrode material
- High battery cost has been a concern

- **Result is that no one can afford to do R&D on better recycling processes**

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Lithium Recycling Progress

- A batch process for extracting lithium from lithium battery waste has been characterized.
- Continuous extraction processes that are more compatible with continuous lithium carbonate production methods are now being studied.
- Samples of battery waste have been characterized in order to identify contaminants that are incompatible with the waste in the processing environment.
- The implementation schedule for an optimized lithium recycling process is still uncertain.

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